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CERTAIN PHASES OF MEGATECTONIC GEOLOGY

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ABSTRACT

A distinction is drawn between structures of ordinary dimensions under low pressures and structures of continental dimensions under high pressures. These are discriminated by the dominance of solid (idiomolecular) flow and the transition of one elastic state into another. Back of these and other distinctions drawn, the special objective is the support of the continents. The ultimate building units, the atom, the molecule, and the crystal, are defined on the basis of the new view of matter. The producing zones of these and the weaker building materials are sketched, unqualified rigidity is denied existence, and the yield factor in elastico-rigid bodies critically discussed. The distinction between rest stages under stress-balance (elasticostatic) and hydrostatic equilibrium is emphasized; elasticostatic configurations are compared with hydrostatic and illustrated by the warpings of the "sea-level" due to the solid shell. The superficiality of this is shown, and its unfitness as a test of continental support. The real criteria are found to lie in base-leveling, sea-transgression, parallel deposition, periodic diastrophism, Eulerian nutation, body tides, and internal transmission of seismic waves. These are discussed and the conclusion reached that the "floating crust" is a misinterpretation, that no hydrostatic substratum has prevailed since base-leveling began, that the earth-body is a heterogeneous elastic solid, that internal reorganization is the dominant agency in terrestrial reconstruction, that the earth is better organized and stronger today than ever before, and that the processes of reorganization show no signs of exhaustion.

Whatever relates to the architecture of the earth falls under the broad mantle of tectonic geology, whether it concerns building material, or construction, or collapse. But between the earth's greatest and its least structures there is a wide range in size, mass, stress-magnitude, and structural organization. There are, to be sure, gradations from the least to the greatest; but the range in magnitude involves differences that are scarcely less than radical. There is,

therefore, need for some device that will enable one easily to indicate his meaning when speaking of conditions greatly surpassing those commonly implied by ordinary tectonic phraseology. My discussion will relate chiefly to segments whose breadths and depths reach thousands of miles, and whose stresses and modes of yield reach a like order of magnitude. I am, therefore, venturing to use the term "megatectonic" to indicate structural considerations of this high order of magnitude.

The leading principles of structural geology, in the usual sense of the term, have recently been admirably set forth by Leith,[1] Willis,[2] and others. It is no part of the purpose of this paper to enter this well-cultivated field. Some of the finest studies in this line have just been given to the scientific public through these pages. In these standard works and in these admirable papers, such considerations as pertain to the zone of observation have a distinctly preferred place. Their limitation to the zone of observation is in some cases rather strongly emphasized, while considerations that involve interior conditions are less amply recognized and their more uncertain nature is somewhat stressed. While this discrimination seems to me wise in texts for students and busy geologists, the wholesome restraint intended should not be interpreted as casting a shadow on comprehensive studies of the earth body, even though some of the fields involved are not in every sense accessible or amenable to tangible evidence. In my judgment, the importance of the fundamental questions of the earth-body is so great that as much emphasis as reasonable care and caution will permit should be laid on all legitimate evidence, even if pioneer in nature and necessarily somewhat tentative, for, consciously or unconsciously, views of some kind relative to the state of the interior will and actually do steal into the interpretation of ordinary tectonics, and these are quite sure either to have their source in some form of inherited assumption without revision or to be the product of conscious revision in the light of later data. Besides, the heretofore hidden fields are rapidly falling under the light of a new zone of observation.

[1] C. K. Leith, *Structural Geology*, rev. ed. New York: Henry Holt and Co., 1923. Pp. 290, figs. 103.

[2] Bailey Willis, *Geologic Structures*. New York: McGraw-Hill Book Co., 1923. Pp. 296, pls. 10, figs. 121.

THE RECENT EXTENSION OF THE ZONE OF OBSERVATION

The interior of the earth is no longer a realm of darkness and mere speculation. Three lines of specific evidence now penetrate it. While their full import is not yet at command, important light has already been shed on the tectonic state of the interior. The three sources of evidence are: (1) the geographic or Eulerian shifting of the axis of the earth (the "wabbling" of the poles), which not only shows that the earth as a whole is a highly elastic solid but that its elasticity is responsive to slow-acting stresses; (2) the behavior of the body tides, which also shows that the earth as a whole acts as an elastic solid and responds with singular promptness to stresses that come and go gradually; (3) the traversing of the interior by the second set of preliminary earthquake waves. These waves have now made a sufficient number of legible records of the conditions along their paths through the interior to bear very trenchantly on the concept of a floating crust which still so deeply penetrates tectonic literature.

These three lines of light are shed by independent phenomena, and when correlated with geological considerations, go far to take the interior out of the sphere of mere speculation and to place it in the realm of specific scientific inquiry on approved lines.

THE BORDER LINE BETWEEN ORDINARY TECTONICS AND MEGATECTONICS

There is, of course, no sharp dividing line between tectonics of the larger and the lesser order; but there is a transition zone that is worthy of the closest study. The megatectonic state may be said to replace the ordinary tectonic state whenever (by reason of dimensions or depth or special stress) idiomolecular reorganization and solid flow take the place of fragmental and liquid flow, or more specifically whenever, under increasing stress, one elastic state gives place to another elastic state, instead of breaking down by fracture or by liquefaction. The term "idiomolecular" is here used in a generic sense to include all intimate reorganization taking place either atom by atom, or molecule by molecule, or by any other simple unit replacement, if there be any such. It is individualistic action and is distinguished from pell-mell action by groups of atoms or molecules such as constitute liquids and gases. In the transition

zone between the surface and the depths, structures break down variously by fragmentation, by liquefaction, by vaporization, by different modes of shear, and by idiomolecular reorganization. When with increasing depth the stress conditions rise to such a degree of intensity as to restrain effectively fragmentation and liquefaction and force reorganization, the megatectonic zone may be said to have been reached.

FORMS OF FLOW

As indicated, three types of flow are involved: (1) fragmental flow, (2) fluidal flow, and (3) solid flow. In the last, the main structure remains solid at all stages; the reorganization movement is accomplished by the transfer of individual atoms or molecules from one fixed attachment in the solid structure to another, thus slowly reconstructing it and at the same time shifting its mean position. This is a slow process, but singularly well adapted to shifting structures without causing their collapse. It only becomes very effective when promoted by adequate differential stress, though it appears to take place to some extent under all natural states of pressure. Idiomolecular action is also promoted by heat when that merely approaches liquefaction but does not reach it.

Looked at from the point of view of stress, the matter may be put very simply, if a little repetition may be pardoned. In the outer zone of the earth restraining stresses are relatively low, so that when the forcing stresses rise beyond the elastic limit, the sequences are uncertain: sometimes there is granulation or some other form of collapse by fracture, including some types of shear; sometimes there is liquefaction or change to a viscous or semi-liquid state; and sometimes there arises a new elastic state by atomic or molecular reorganization. But with increasing depth and load, horizons are reached in which the restraining stresses become relatively high, so that fragmentation and liquefaction are largely inhibited, and reorganization flow or solid flow becomes the normal mode of accommodation to forcing differential stresses.

DEPTH OF ZONE OF REORGANIZATION

It is my belief that this zone of idiomolecular reorganization extends to the heart of the earth, and that it thus includes the whole

downward extent of the continental and sub-oceanic segments and the core besides. The motion within this reorganization zone is glacier-like, but silicates and their allies require a higher degree of differential stress than ice to make the reorganization motion effective. The normal state of rest or quiescence, when motion practically ceases, is elasticostatic, not hydrostatic, that is, the horizontal components of gravity are not equalized as in hydrostatic equilibrium, but are balanced by elastic stresses called forth by strain. The remnant of horizontal gravity-stress is balanced by strain-stress. They thus form a type of stress-balance.

In the deeper zone of the earth, some interstitial liquefaction and some threading of liquid matter outward is also recognized, but this is regarded as quite subordinate in amount to the prevailing solid state, while open fracture and fragmentation are held to be limited to moderate depths.

(I hold that a state similar to this affects the core of the earth, but that is beyond the limits set for this article.)

As some of the foregoing distinctions may not be altogether clear, or may not seem true, or may not appear important, they will be treated more fully (at the risk of some repetition) in the course of the article, and an effort made to show that they are indispensable to dynamic geology revised on the basis of the new views of the constitution of matter. They are here bunched and briefly stated to give emphasis to the distinction between the megatectonic conditions involved in the great structures and the less strenuous conditions of more surficial situations.

RELATIVE COMPETENCIES

It scarcely need be said that the greater the stress, the severer the test of competency of the building units involved, and hence the megatectonic requirements are severer than those of the more surficial tectonics. As a rule, secondary structures are less competent than primary ones. At any rate, the first step in considering the competency of the building material of so large and complex an edifice as the earth is an examination of the ultimate building units of which it is constructed, the atoms and molecules.

THE FUNDAMENTAL BUILDING UNITS

So far as the architecture of the earth is concerned, it is not necessary to seek for a primary building unit below the atom, though the atom is not now regarded as strictly elemental. The activities of the sub-atomic units are far too intense to be controlled by the gravity of the earth, unless they are tied up in some way with the atom or its compounds. It is necessary, however, that the inherited picture of the atom be radically changed, if we are to be in accord with the well-supported discoveries of the physicists and chemists in the last two decades. This change must include not a few derivatives from the old picture also. Even at the risk of some error and the certainty of some need of revision, it is better to put ourselves in the line of coming truth than to hold tenaciously to inherited tenets —particularly if these tenets, in addition to their discordance with physico-chemical revelations, also fail to fit new tectonic requirements disclosed by new lines of study of the earth itself. The former conception of the structure of the atom seems to have been the source of certain tectonic misconceptions that now stand in the way of a better insight into tectonic fundamentals. The former picture of the atom as a minute, smooth, hard, incompressible, indivisible spherule, led to concepts of excessive rigidity. These were lacking in a due sense of elastic yield, or yield of any kind. As the integer itself could not yield, its motions relative to its neighbors consisted wholly of gliding and rolling, and this gliding and rolling furnished the basis for the picture of flow. But this is too simple an ideal of flow, as we shall presently see. It was too rigid on one side and too loose on the other. From these too rigid and too simple gliding and rolling concepts arose the ideas of easy liquidity and unqualified rigidity that have permeated geological thought and literature up to the present. The basis for these is now discredited. We face the task of replacing these discredited concepts with the best ideas of the structure and building qualities of the ultimate units that are now available. We may be certain these will be imperfect, but that is no reason why we should not replace the bad with better.

THE NEW CONCEPT OF THE ATOM AS A TECTONIC UNIT

Instead of an ultra-materialistic spherule, the new revelations offer a dynamic mechanism in which matter, in the old sense,

practically disappears, or at best becomes only a convenience of thought, and electric units in revolution about one another take its place. These of course carry the attributes of revolutionary bodies and may be said to bring celestial dynamics in a diminutive form into our study. The tectonic unit comes to have more nearly the properties of a coiled spring than of an ultra-hard spherule. The concepts of absolute rigidity and incompressibility must be cast aside and qualified senses of these properties, carrying a yield element, substituted for them. Bodies in revolution yield to stresses of all degrees, as shown by the perturbations so universal in celestial bodies. Notwithstanding this yield factor, the leading property of revolutionary bodies is fixity of orbit and general stability. As orbits cannot be handled, the gyroscope may be taken as a substitute. In addition to the properties springing from the revolution of neutral bodies, the revolution of electric charges gives rise to magnetic fields and magnetic polarities. These afford an excellent basis for a picture of the fixities of attachment, the elasticities of hold, and the restitutional stresses that so definitely characterize both ideal electromagnetic and elastico-rigid bodies. Thus the atom, by its very constitution, becomes a standard type of a yielding body which is sensitive enough to respond to any force and yet holds in reserve and subject to call a stability of a very high order. The extraordinary velocities of the revolving integers give the atom extremely high gyroscopic stability and gyroscopic elasticity. The polarities, arising from the equal swiftness of the electric charges, give similarly strong fixities of attachment or of position. Yet both stability and fixity are mated with the elastic factors and for convenience may be said to be elastic. The special influence of this elastic factor thus comes to have a function in all tectonic problems. It is helpful to think of the atom as the ideal elastico-rigid body. It is a serious error to overlook the elastic factor and attempt to deal with megatectonic problems on the basis of unqualified rigidity, for unqualified rigidity is now without known or even probable existence in our universe.

THE MOLECULE AS A TECTONIC UNIT

Were there space, it would be helpful to dwell on the atoms long enough to recite their habit of forming themselves into combinations of much complexity. They are not only revolving mechanisms

but multiple mechanisms. The changes which these combinations may yet prove to be undergoing in the earth, in addition to those they are known to be undergoing, may be important factors in the tectonics of the earth. Passing these as mere possibilities, the well-known combinations of atoms into molecules give both demonstration and emphasis to the fixity of the atoms in definite positions, and to the profound influence of this on the properties of the combinations so formed. If there is any shadow of doubt about the electromagnetic concept of polarity, the fact of polarity of some kind is amply affirmed by the data of stoichemistry. Molecules, like atoms, are ideal types of elastico-rigid structures.

THE CRYSTAL AS A TECTONIC UNIT

In the atoms and molecules the elastic fixity of the units is beyond direct vision; it is merely a matter of firm inference. In the crystal, however, through the good offices of the X-rays in the hands of Laue, the Braggs, Wyckoff, and others, the space lattices are shown to the eye. This completes the connection between microphysics and geology, for crystals stand as the dominant type of earth-matter in the zone of observation, and overwhelmingly so, by inference, in the inaccessible portions. Not only do the space lattices reveal the orderly arrangement of the atoms and molecules in crystals and their positional fixity, but they disclose a remarkable openness of structure. It is greatly to our convenience and comfort that we are not left to the resources of our rational imaginations to picture the mode by which revolving electric units can give rise to angular arrangements of the units in space, nor how they are held there. Led by the visible facts, we can see that it is all logical enough, but it might have been something of a strain had not the short waves tangibly demonstrated it. The openness of structure reveals how truly the earth's tectonics rest on fields of force and not on ultra-rigid units. Compressibility, so far as earth structures are concerned, now appears to be simply a matter of adequate compressing force, not a matter of inherent limitation.

WEAKER AS WELL AS STRONGER TYPES OF TECTONIC UNITS

The elastico-rigid or yield-fixity property that dominates the intimate structures of the atom, the molecule, and the crystal, and

takes on tangible expression in the angular forms of the latter, I believe to be the great basal type of tectonic formation, not only because the crystalline structure greatly preponderates over any other one form of known structure in the zone of observation, but because this structure is so close to the mechanism of the primary integers in the innermost field of formative action. The crystal is next akin to the molecules and atoms. But let us set this aside for a moment, and take note of a quite prevalent tendency of earth substance to take on spheroidal forms under certain conditions. We must be content merely to form the best concepts we can as to how this tendency arises and what it really means. We cannot expect full demonstration in many particulars until a more advanced stage of investigation has been reached.

THE FACTORIES OF THE BUILDING MATERIALS

With a little repetition, for a good start, let us begin with the innermost factories where atoms, molecules, and crystals are formed, and work outward. Let us place our reliance chiefly on the producing agencies, as these seem now to be fairly well established. Looked at dynamically, there seem to be three producing zones: (1) an innermost zone of intense forces, (2) a transitional zone of mixed forces, and (3) an outer zone of dispersive or de-tectonic forces.

1. *The innermost zone.*—It appears from what has already been said that in the innermost zone, close about the atom, the controlling forces have intimate combinations of elastic yield, of strong potentialities of resistance and recovery, and of strong position-fixing polarities. While the mechanism is revolutional, the polarities give rise to fixed positions in angular arrangements. It is an inference from this that the closer the structures are compressed about their atomic centers, the more completely will this type of organization prevail. This is supported by the fundamental principle of celestial mechanics, in accordance with which the more orbits are reduced, without addition or subtraction of momentum, the higher their velocities, and all that goes with velocity of revolution. If electrically charged, the more intense their electromagnetic polarities. This makes vivid the reason why compression tends to give true solidity to normal types of organization, as shown by abundant experimenta-

tion in spite of the not unnatural notion that the heat of compression would give rise to liquefaction.

2. *The middle zone.*—As electromagnetic units are separated from one another, the contacts of their polar fields naturally grow feeble progressively, and at the same time grow more spheroidal. It is not difficult to picture a stage of such separation at which fixity of attachments and strength of elastic hold are replaced by the more general attractions of the adhesive-cohesive type, whose attachments are indifferent as regards position and which have no tendency to recover previous positions. This is equivalent to defining the conditions under which viscidity and liquidity prevail. This gives us a tangible basis for seeing how the viscid and the liquid states may grade into the elastico-solid state. This is not claimed as a demonstration, but merely as a consistent picture. The gradation from the inner to the middle field may be attended by various degrees of declining elasticity and rigidity. On the borders of the inner field these may mount to a state of quasi-solidity.

Heat is the most familiar form of energy by which such separation is effected, and it follows that temperature is a very critical factor in this zone, but it does not follow that it is equally critical everywhere. A part of the effect of heat may be simple separation and a part simple agitation such as to make a steady hold precarious.

3. *The outer zone.*—Following the same gradation of forces outward, a zone is reached in which collisional repellencies overmatch the attractions of the cohesive group and the constituents tend to fly apart except as they may be held by the enveloping gravity of the earth. This may be said to be an anti-tectonic state, though it is a source of feeding of certain structures.

It may be added here that liquids and gases are merely states of assemblage of atoms and molecules; they are not organizations of them, as crystals are. They belong to a distinctly lower tectonic grade. The crystalline unit is about as definite an organization as an atom or a molecule. Liquids rank next and may be likened to harmonious-minded crowds whose habit is to work together with a fair degree of harmony and more or less efficiency. Gases are like jostling, riotous mobs in which disorderly action and hard hitting are the order of the day.

THE TEMPERATURE FACTOR

It was noted above that in the middle zone—the relatively narrow zone of liquidity—heat is a critical factor, but that it is not necessarily so in other zones. Important as it is, in its own rather narrow field, probably no factor in terrestrial dynamics has been the subject of so much misplaced confidence as heat. It has been foster-father to a long list of discarded views, ranging from a gaseous interior to the master-force in the earth's evolution. Its function has been greatly exaggerated and its trustworthiness as a basis of deduction greatly overestimated. Though the new views of the constitution of matter have greatly increased our realization of the resources of energy in the earth, it has chiefly been energy of the revolutionary type. Heat has been demoted to a mere incidental class, that of merely transient phases of energy, alternately developed and destroyed, as incidents of the formative processes. The total thermal energy in the earth (on the highest tenable estimate) bears an exceedingly small ratio to the total energy now known. But the chief source of misguidance lies in the alternative paths which heat takes in connection with the great earth processes, the one path being a continuance in agitative and dispersive work, the other being a return to a constitutional form of energy and consequent disappearance as heat. So imperfect as yet is our knowledge respecting this vital partition of energy that deductions based on temperature are highly precarious.

ANALOGOUS ZONES OF EARTH STRUCTURE

There is more than a mere fanciful analogy between the zoning of the dynamic fields surrounding the atom and the zoning of the field that surrounds the center of the earth edifice. Of course, the analogy may easily be pressed beyond its legitimate limits. As we have just been considering the outer field of the atomic series, let us start with the outer field of the earth series, and reverse our order.

The atmospheric annex.—In the outer field of the earth's control there is a zone a million kilometers deep in which agitation gives the constituent units a tendency to escape. The whole atmospheric annex is due to gravitative compulsion. Considered as builders, this is a belt of slave workers whose individual balances of credit and debit are rather doubtful.

The water mantle.—Within this, and more closely adherent to the true earth-organization, is a liquid layer carrying in solution some matter of the same order as that of the solid body. This is really only a mantle, and even as such only partially covers the solid body. Like the middle zone about the atom, it is thin spacially, while in origin and structure it is intermediate and dependent. It is little more than a contact film between the dispersive zone above and the constructive sphere within. While its importance from the human point of view is beyond exaggeration, its importance as a factor in the tectonics of the earth is liable to be much overstressed.

Both the liquid layer and the gas envelope penetrate the solid body of the earth to some extent, and, uniting more or less with its solid substances, help to form a complicated contact zone. This is a zone of conflicting processes, at once a zone of degradation and of reconstruction. The work of disintegration, erosion, transportation, and deposition is actuated chiefly from without; the main residues are arranged stratigraphically. But these stratiform sheets are cut through and at the same time interlarded and bound together by igneous tongues from within. This zone is thus the scene of tectonic unmaking, making, and remaking. The result is a shell of riveted stratiform structure. The main products of the external forces are stratiform sheets of worn and weathered surface materials; the main constructive work from the interior has been a thrusting of igneous tongues into the sheets and a spreading of these out within or upon the sheets, taking on tack-head-like enlargements, thus hot-riveting them into a jacket written all over with the earth's history. Diastrophism at intervals recut and folded this jacket, but diastrophism is a little aside from our main theme though close akin to it.

The solid but constantly reorganizing sphere.—I follow here the hypothesis that the earth grew up very deliberately by the infall of planetesimals. The leading alternative views are too familiar to need recital. According to the planetesimal view, the original state of the main mass of the earth was minutely clastic and very heterogeneous, but as it became buried by its own growth, reorganization of the heterogeneous mixture set in and has been the dominant structural activity of the interior ever since. Tectonically this reorganization

was, mainly, a change toward greater solidity, strength, density, and stability.

NEGLIGIBLE BUILDING MATERIALS

The material of the outermost zone of the earth-body ranges from that which is declaredly crystalline to that which is fully fluidal, that is, from the most systematic and best organization of the constituents to a state which has no fixed organization at all. Between this best and this poorest of building materials, there intervenes a series of substances of ill-defined qualities which one can scarcely designate accurately even by naming them, for their names, like the substances themselves, lack definiteness, since they merely designate some one state of forms that grade into allied forms. They are commonly referred to as viscous, plastic, amorphous, etc. They may be grouped as semi-liquid-semi-solid intermediaries. An attempt to analyze them seems to disclose at least seven types, and even these run together indefinitely into no end of permutations and combinations. (1) Among these there seem to be true intergradients, that is, bodies in which certain degrees or phases of polarity are combined with certain tendencies toward sphericity, as in the wonderful structures of the biologic world. (2) There are comminuted solids suspended in fluids, forming a class of colloids found abundantly in soils and surface waters. (3) There are solutions containing viscid elements whose stages of concentration give strength to the adhesion-cohesion factor in varying degrees without showing any distinct polarity or preferential attachments. When such binding is strong enough, a sudden stroke may call into temporary action the elasticity of the constituent atoms and give a resonance that resembles that of elastic-rigid bodies. (4) Incipient crystals may be formed in cooling viscid liquids of types which crystallize fully when given adequate time, but which with rapid cooling are caught by the increasing viscidity in such early stages of their growth that they are not visible but yet take on most of the qualities of an elastic-rigid body except that of full orientation, as in the glasses. (5) Under ordinary conditions of pressure, the molecules of molten rock tend to arrange themselves in one of the forms of greatest compactness and if held in this state by any suitable container manifest distinct properties of rigidity as brought out in the beautiful studies of

Mead.[1] (6) But when the compression is considerable the molecules may wedge themselves between one another and thus form close contacts that act much like the fixed attachments of genuine elastic-rigid bodies; indeed they probably grade into such bodies. They may thus become quasi-solid bodies. (7) When complex molecules are pressed together beyond the limits of their normal spheres of mobility they may interlock, as recently suggested by Bridgman.[2]

As a rule, these intermediate forms are poorer building material than the crystalline phases of the same substances. Moreover, varied and numerous as these intermediate substances are, they really amount to little compared with the crystalline matter, even in the outer ten or twenty miles of the earth-body, usually regarded as fairly well within the zone of observation. They may well be regarded as negligible in a megatectonic study. They are little more than the inevitable weatherings of the exposed surface of the earth edifice.

THE YIELD FACTOR

From the tectonic point of view, the most important qualities lie in the structure's power of resistance and in its liability to yield. Let us therefore now turn to this critical phase of the subject. Three forms of flow have been mentioned, liquid flow, flow by fragments, and solid flow. I think that the crux of the issue respecting continental support lies in the last, which needs all the elucidation that can be given it.

SOLID OR REORGANIZATION FLOW

An intimation of the nature of solid or reorganization flow has already been given, and the process has been elsewhere described,[3] but the precise sense in which the term is here used is not yet familiar enough generally to warrant the resting of so important an issue on it without further elucidation. To call any movement solid flow seems something of a paradox, but the phrase has already found

[1] Warren J. Mead, "The Geological Rôle of Dilatancy," *Jour. Geol.*, Vol. XXXIII (1925), pp. 685–98.

[2] P. T. Bridgman, *Proc. Nat. Acad. Sci., U.S.A.*, Vol. II, No. 10 (1925), p. 606.

[3] "Diastrophism and the Formative Processes: XV, The Self-Compression of the Earth as a Problem of Energy," *Jour. Geol.*, Vol. XXIX (1921), pp. 679–702, particularly pp. 697–99.

a place in geologic literature and has advantages as well as disadvantages. But the term is sometimes used so broadly as to include flow by fragments. This, however, is quite distinct from idiomolecular flow, and will not be used in this article, because fragmental flow is quite a surficial matter and has little to do with megatectonics. Solid flow, in the sense of flow by reorganization, is really a form of growth following disaggregation. It is a serial reorganization, one integer after another changing its place and attachments. The action is individualistic (idiomolecular) in distinction from communistic (all-together) action, such as takes place when assemblages of molecules move pell-mell (liquid-flow), or by heterogeneous tumbling, as in the flow of sand and talus blocks (fragmental flow).

In the variety of solid flow which has been called idiomolecular, the main mass of the body remains stationary and solid while individual atoms or molecules that happen to be under special stress because of their positions at angles or otherwise are forced from their points of attachment and given sufficient projections to penetrate the surrounding field of force far enough to find new attachments and again become a part in the structure. By this shift, the most intense stresses are relieved and the new attachments help to adapt the structure to the remaining stress. Far from really being paradoxical action, it is a specially orderly, soldier-like action to relieve the outpost under greatest pressure.

SHIFT FROM ONE ELASTIC STATE TO ANOTHER

There is another phase of this reorganization flow that may be given an even more paradoxical phrasing than the flow itself. Under conditions of general confinement and stress a crystalline rock often "breaks down into a stronger elastic solid." This does not hold true in all cases of molecular shift, and is perhaps not the most common case near the surface where general pressure does not stand in the way of liquefaction or breaking down fragmentally, but it seems to be the rule at considerable depths, and these depths are the ones that most concern us here. When a particular atom or molecule is forced from its exposed position by some one of the special stresses so likely to arise in the depths under confinement, and is projected

by special force arising from the special stress, so that it makes a new attachment elsewhere, this new attachment is quite likely to be better than the previous one, for among other things not easily stated in a word, the molecules that are temporarily free tend to unite with large crystals rather than small ones; and to build out crystals into interspaces so that they fit into one another more firmly. The general fact of such increase of strength as reorganization flow goes on is familiar enough but it has not been adequately recognized in this sense nor duly appreciated. As a rule, a glacier grows stronger by reason of reconstruction as it flows from its very weak granular state in the snowfields toward its relatively solid state near its terminal moraine. A mud bed grows stronger by the organization that sets in as soon as it is laid down. It continues to grow stronger until it passes into a shale; a shale becomes stronger as it is further organized into a schist. The weaker class of schists usually pass by recrystallization into schists of stronger types. There may be exceptions when massive crystalline rocks are broken down into schists, but increased strength seems to be the average effect. This holds good even in the upper part of the zone of observation. There are additional reasons for believing that, in the deeper horizons, this glacier-like reorganization flow is distinctly the dominant type.

Considered from the tectonic point of view, solid flow is a process by which an edifice is moved and at the same time more or less largely rebuilt into a stronger structure in the very moving process.

THE STATE OF REST FOLLOWING SOLID FLOW COMPARED WITH THAT FOLLOWING LIQUID FLOW

While reorganization takes place in some measures in sediments without more than the differential pressures common at the surface (and probably takes place to some extent without any outside stress at all), effective solid flow in strong rocks requires a somewhat high degree of differential stress. As already noted, less stress may be required when temperature aids the flow. As a protruding body like a continent flattens by flowage, the differential stress within it slackens by the lowering of the gradient. The flow responds to this by slackening also. At a stage of sufficient lowering of this gradient the flow practically ceases. This will take place before the differen-

tial stress is completely eased. It is observed, as in the Malaspina and other glaciers, that the ice takes the form of a spreading foot, the surface of which does not reach a "dead level." If the mass is a spreading continent, the flow will stop much before the horizontal component of gravity reaches zero. The residue of this horizontal component will be matched by strain-stress in the sloping border of the continent. Thus there arises a stress-balance between the horizontal component of the residual gravity and the elasticity of the material that had ceased to flow because the difference of stress within it had become insufficient.

It is easily seen that this state of stress-balance is not identical with hydrostatic equilibrium. To reach hydrostatic equilibrium, the horizontal component of gravity must be fully eased. Unless it becomes zero, there is no equilibrium of gravity.

Even in that form of crystalline rock which flows easiest, ice-rock, there remains a notable stress-balance shown by the failure of ice to flow until it reaches a "dead level." In the case of average crystalline rock, the terminal slope shows a much more considerable stress-balance when flow ceases. The stress in the rock which balances the uneased horizontal component of gravity arises from the elastic strain of the rock mass (with the exceptions above considered and herein neglected). For the state of relative rest under elastic strain when appreciable movement ceases there is perhaps no better term than "elasticostatic," simulating the form of hydrostatic, the state of rest of water-like liquids in which the horizontal component of gravity is zero.

ELASTICOSTATIC VERSUS HYDROSTATIC CONFIGURATIONS

When the masses of rock are very large, as in the case of continents, the elasticostatic state takes on a configuration not very different from the hydrostatic configuration. The difference may not be conspicuous except at the continental borders. But the difference, whether conspicuous or not, is highly important. It involves the essential distinction between the rest states of great masses of solids, on the one hand, and the rest states of masses of liquids, on the other. The protrusions of continents above the sea-level depend upon it. How different the elasticostatic and the hydrostatic states

are in the constitution of the continents may easily be pictured to the imagination by supposing the existing solid rock to be converted into liquid rock and watching the catastrophe that would follow.

This simple illustration of the difference between the actual elasticostatic state and a hypothetical hydrostatic state further illustrates how very special is the sense intended when the continents are said to be in a state of hydrostatic equilibrium. This very partial sense is so liable to mislead that we must consider it further and as far as possible in the zone of observation.

THE ELASTICOSTATIC AND THE HYDROSTATIC IN THE ZONE OF OBSERVATION

Within the zone of observation the elasticostatic state is represented by the riveted shell of the earth; the hydrostatic state by the water mantle. (There are scattered spots of liquid rock, but these are small and temporary.) There is no question as to the mastery of the shell over the mantle in respect to tectonic strength and to relative proportions of yield, when the one is matched against the other. The water mantle adjusts itself to the shell both at the bottom of the mantle and also at its top. The sea surface is warped by the irregularities of the local attraction of the shell beneath it and at its sides. The horizontal gravity-pull of the oceans on the continents is just the same as that of the continents on the oceans; action and reaction are equal and in opposite directions, but the yield of the continents is negligible, while the yield of the water gives the sea-level a distorted surface. The handling of this distorted surface is one of the most intricate and subtle of all earth-problems.

The "sea-level" is constructively extended under the lands where a part of the solid body is above the "sea-level," and this adds to the complications of the case. But the most insidious factor lies in the fact that the data of observation are dynamic, and as such, direct and perfectly reliable, while the geometric aspects that usually take precedence in our thoughts are only derivations (tangents, etc.) and are prone to run at once into error and as a matter of fact do so. We think of the geometric, but we use the dynamic. It is the local dynamic level and the local dynamic vertical that are used in the practical arts, industries, and sciences. These local dynamic guides

are eminently trustworthy, but the geometrics taken off from them run so rapidly into divergencies that their true relationships to the form of the earth as a whole involve the most formidable difficulties.

THE DISTORTION OF THE SEA-LEVEL AN EVIDENCE OF SOLIDITY

The "sea-level" is not only warped by the irregular attractions of the solid shell, but it is warped in two styles: in the one, the shell is below the water mantle at some distance; in the other, the "sea-level" cuts through the shell protrusions, and is the product of shell-pull from both sides. Furthermore, some of the differentiating masses make the closest possible approaches to the "sea-level" plane, so that not only are the gravity-distortions intensified but they are made to merge into those called adhesive, cohesive, and capillary. This may seem pressing the case pretty far, but we are after the principles and the realities of the case, and differences of distance play a very radical rôle in the inequalities of gravity at the surface, such as are revealed by the spirit level, the plummet, the seconds pendulum, and similar means. The force of gravity varies inversely as the square of the distance. A mass whose center is distant 1 kilometer has 100 times the force of the same mass at 10 kilometers distance, and 10,000 times the force of the same mass at 100 kilometers distance. Thus the special effects of varying density in the outer earth body practically vanish at quite shallow depths. Even if it were possible to distinguish the liquid state from the solid state by differences in their specific gravity at a distance of 1 kilometer—for example, in the base of a volcano—such a discrimination could claim no confidence at a depth of 10 kilometers, much less at a depth of 100 kilometers and below. The differences between the densities of the liquid and the solid states at a short distance below the surface fall below the probable errors of determination in such a case. Moreover, it is one of the special functions of liquidity to destroy such irregularities of density and thus cut the very ground from under such discriminations. The very conditions of the case seem, therefore, to shut out the possibility of deriving from surface peculiarities of gravity any cogent evidence respecting liquidity or hydrostatic equilibrium under the continents.

THE PRIMARY VALUE OF THE SURFICIAL INEQUALITIES OF GRAVITY

While there are inequalities of gravity of all orders of magnitude and penetration up to the regional, the continental, the hemispherical, and the total, the law of gravitation gives extraordinary influence to surficial inequalities of density. The observed irregularities are therefore in the main signals of variation in the density and the position of solid matter near the earth's surface. They are specific tokens of solidity, for they would disappear if the shell were made thoroughly liquid and kept liquid for a geologic period. As local signals of what is hidden near the surface, they are geological assets.[1] To make the most of them, they should be individualized and defined so far as practicable. The working of these out into the specific details of a good contour map of the gravity dynamics of the surface would be a fine attainment. To reduce them as though they were troublesome "anomalies" is like the wiping off of the hills from a topographic map. When the peculiarities of the local gravities have been thus discriminated and depicted to get their real meaning they would be in the best possible condition to be merged into a generalization that shall disclose the form of the geoid.

REAL TESTS OF THE CONTINENTAL FOUNDATIONS

Substantially all views of continental support fall into two genera: (1) those which in some form postulate a floating crust and a mobile substratum which supports the continents hydrostatically, and (2) those which postulate a solid earth structure of which the continents are simply the protruding portions.

1. The liquid-hydrostatic theory is about as old as geology and quite familiar.

2. Solid support excludes hydrostatic support except in a loose and very special sense of the term, which if used should be specially indicated and defined. A solid state derived from a molten state seems to me shut out by the differences in density between the continents and the sub-oceanic segments, for the continents cannot be in hydrostatic equilibrium with the sub-oceanic segments unless there

[1] David White, "Gravity Observations from the Standpoint of the Local Geology," *Bull. Geol. Soc. Amer.*, Vol. XXXV (1924), pp. 207–78.

has been a differentiation of material of segmental proportions. No adequate source of differentiation of this order of magnitude could apparently have arisen from a liquid state of the earth. But they would arise inevitably from planetesimal growth. As the products of such growth, the continents are held to be thick obconical columns wedged between still broader sub-oceanic segments. All these segments are held to rest on and to grade into a solid core, of even denser and stiffer material, both core and segments being in an elasticostatic state of stress-balance. When they move at all, it is by solid reorganization flow. It is a part of the view that the continental columns were originally the lighter and the more protrusive and that they have always remained so; so, also, that the heavier columns have always been undergoing loading and hence taking precedence in sinking and in underthrusting the continents, thus not only preventing their collapse but forcing them relatively upward at intervals, insuring their periodic rejuvenation.

The contrast between the two views is radical. Let us scrutinize them a little more closely with a view to finding tests of their validity.

1. *The postulate of a crust floating hydrostatically.*—The first view was derived logically from the theory that the earth was originally molten. It is generally agreed that cooling from a molten state would only give a crust of moderate thickness during the history of the earth. Besides, if the crust is to yield hydrostatically in any permissible sense of the term, it must be relatively thin and the liquid layer beneath must be deep enough and fluent enough to transmit stresses hydrostatically. The crust has usually been assigned a depth of a hundred or a few hundred kilometers. Let such a thickness be granted as best fits the hypothesis. The breadth of the continents may be taken roughly at 3,000 to 6,000 kilometers, and the intervening basins at 5,000 to 10,000 kilometers. Assuming that one-half of a continent unloads débris and solutions into half the adjacent ocean, the average unloading area would have a breadth of 2,250 kilometers and the loading area a breadth of 3,500 kilometers. The curvature of these crust-sheets is too low to give any appreciable support; besides, the surface of the crust near the junction of the continents with the basins is often concave upward, and is a line of weak-

ness in other respects. It may be likened to a hinge-line between the loading and unloading sections. With unloading and loading areas of such dimensions supported only by a weak thin sheet lying on a mobile substratum, it is clear that the crust must yield practically *pari passu* with the progress of the loading and unloading. We do not need to argue this for it is practically a postulate of the hypothesis. Granting the premises, the conclusion is incontestable. A steady yield or a yield at short intervals, as the transfer of load proceeds, thus becomes a criterion of this theory. Otherwise, the yield could not be hydrostatic. Of course, short halts and starts due to such small crustal rigidity as is consistent with the main claim may be conceded, but these can have only small value without vitiating the theory.

2. *The theory of solid support.*—In this no crust at all is postulated. Nor is any material part of the continental support made to depend on the strength of the riveted shell. The primary support lies in the thick deep columns; the ulterior support lies in the solid core beneath these. The columns grow stouter as depth increases and all the segments support one another by crowding toward the center.

Differences in constitution.—Another vital factor in the case is the difference in constitution postulated by the two theories or required by self-consistency. The founders of the molten theory held that the matter of the earth was originally arranged in concentric layers according to specific gravity and that the whole conformed closely to the ideal spheroid of revolution and was covered with a universal ocean of nearly uniform depth. On the assumption of liquidity and hydrostatic control this view was thoroughly logical and consistent. No substantial reason for departing from it far enough to make the continents have one type of specific gravity and the sub-oceanic segments another has been established or even cogently supported. Obviously, such a differentiation would contravene hydrostatic principles and support elasticostatic principles to the extent to which it obtained.

On the other hand, the theory of planetesimal growth made the material of the earth at the outset very heterogeneous, not only because the planetesimals had a miscellaneous distribution, but in falling through the atmosphere they were selectively assorted and distributed and the hydrosphere further assorted them. These agen-

cies obviously led to inequalities of growth. These inequalities of the original formation stand in sharp contrast to the symmetries appropriate to the molten theory. This difference is a criterion for testing the two views.

Differences in available energy.—It has elsewhere been pointed out that an earth grown up slowly of heterogeneous material would retain more potential energy of position and more chemico-physical energy than an earth which cooled from a molten state. This energy would also be more widely distributed through the mass and be better suited to megatectonic and megadiastrophic functions.[1]

Modes of adjustment to stresses.—The molten theory postulates liquid flow and a hydrostatic state of rest. The alternative theory postulates solid (idiomolecular) flow and an elasticostatic state of rest.

Let us now test these alternative views by the geologic record, remembering that the issue is megatectonic and the evidence should be correspondingly megageologic.

THE MEGAGEOLOGIC TESTS

About a half century ago Powell and Gilbert opened the eyes of the geologic world to the great phenomena of base-leveling.[2] More recently Davis and many others have made contributions to its elaboration and to its establishment. Base-leveling is not only well established on its own grounds, but is besides supported by correlative phenomena such as shallow sea transgression and parallel deposition,[3] and by antithetical phenomena such as periodic megadiastrophism. These are not only definite lines of evidence in themselves, but are consistently and logically grouped. They fit the case singularly well because both the time factors and the dimensional factors are of a very high order of magnitude.

Base-leveling, sea-transgression, and parallel deposition unite in testifying to very long periods of continental quiescence, for only by

[1] "Groundwork of the Earth's Diastrophism." *Bull. Geol. Soc. Amer.*, Vol. XXXII (1921), pp. 197–210.

[2] Although an absolute base-level was seldom reached, but only peneplanation, I prefer to use the original term in this discussion because it carries the meaning stressed in the test so vividly.

[3] Parallel deposition as an evidence of continental attitude is not as familiar as the other three, which are standard doctrines and need no references. A discussion of parallel deposition may be found in the *Journal of Geology*, Vol. XXI (1913), pp. 523–33.

an essentially stationary attitude can these kinds of denudation and deposition be accomplished. While this evidence of protracted denudation in an approximately stationary state of the continent is incontestable, there is also abundant evidence that complete truncation and submergence of the continents never took place in the well-known eras. The base-leveling never went beyond an advanced state of peneplanation and sea-transgression. This is really valuable testimony, though its bearing is less obvious. It shows the case is one of balance and has limitations, but that the balancing factors represent a high order of strength and stability. Before absolute base-levels of the more enduring parts of the continent were reached, stages of continental rejuvenation were inaugurated and great deformations followed (often in grouped rather than single orogenies). The periods of quiescence during which the truncation of the continents took place, and the stages of intervening megadiastrophism by which they were rejuvenated, taken together form a cycle. The former are interpreted as periods of stress-accumulation, the latter as stages of yield.

To give this evidence of stability on the one hand and of yield on the other more concreteness and definiteness, let us consider (1) the average time occupied by the cycles, and (2) the average amount of loading and unloading which the continental structures bore before they yielded.

1. *The time during which loading and unloading was sustained without essential yield.*—About ten of these great cycles have been recognized as occurring during the Paleozoic, Mesozoic, and Cenozoic times. At least two occurred in pre-Cambrian times. It is altogether probable that there were other cycles in the Proterozoic and Archean eras. If we allow four more cycles, or sixteen in all, following the time of the first igneous intrusions that have given radioactive data for estimating time, and if we take the estimate of this oldest determined stage at 16×10^8 years, the average length of a cycle would be about 100,000,000 years. There seems no reason to suppose that the number of cycles could have been double the sixteen allowed, so that if we cut this 100,000,000-year period in half we would seem to be making liberal allowances for imperfection, but to be ultra-conservative, let us cut the estimate in half again and use in

our argument only 25,000,000 years. It is probably a fair apportionment of this to assign four-fifths to the stage of quiescence and one-fifth to that of megadiastrophic rejuvenation; at any rate, the stages of quiescence were much the longer. This gives 20,000,000 years for the average stages in which the continents sustained loading and unloading without essential yield, and 5,000,000 years for the series of deformations that eased the stresses which had accumulated during this period. Even if still more conservative figures were used, the strength indicated would be very difficult to realize.

2. *The amount of matter transferred before continental yield took place.*—If we assume that the present is a stage of major continental protrusion and accept the mean of well-considered estimates of the average height of the continents, and compare this with the state of truncation at the close of such a typical stage as the Silurian, it will give perhaps 1,600 or 1,800 feet as the average depth of material transferred from the continental side to the abyssal side during a typical cycle. Such checks as I have been able to derive from the total denudation and from the total diastrophism seem to indicate that this estimate is at least not excessive.

Now, it seems to me utterly incredible that a floating crust on a liquid layer could have sustained without marked yield transfer of this order for periods of the order indicated.

THE HETEROGENEITY OF THE OBSERVED IGNEOUS EXUDATIONS

There seems to me to be a strong argument against the theory of a once liquid earth in the heterogeneity of the igneous matter that is squeezed out of the body of the earth, at the times of the great diastrophic revolutions, but the argument requires too elaborate a statement to be given a place here. Let us turn to geophysical evidences.

THE TESTIMONY OF EULERIAN NUTATION

While much remains to be learned about "the wabbling of the poles," what has already been learned carries great significance.[1] A

[1] For an illuminating treatment on points pertinent to this article see W. Schweydar (Potsdam), "Über die Elastizität der Erde," *Die Naturwissenschaften* (Berlin), Vol. XXXVIII (1917).

motion of this particular kind would not accumulate and persist if the interior of the earth were liquid or viscous. Such a motion would soon be killed if it should in any way be imposed on such an earth. As nutation of this kind may spring from different sources, it promises to become the most far-reaching of the several evidences of the elastic solidity of the earth, but most of this prospective value remains to be worked out. The nutation is already known to be a secular motion, in a mild sense. It seems to arise, in the main, from the persistent accumulation of the effects of small stresses coming gradually into action. The elasticity it represents cannot be fairly interpreted as "elastic for short stresses but plastic to long ones." In any case, simple yield under long stresses is not evidence against elastic solidity. Yield of a certain kind is one of the standard modes by which one state of elastic solidity passes into another and usually stronger state, as previously set forth.

The nutational curve has been analyzed into a factor that has an annual period and a factor that has a period of about fourteen months. The first has been commonly assigned to changes in atmospheric circulation, precipitation, and other effects that arise from the seasonal shifts of insolation. There is less unanimity in interpreting the longer period. The explanation of the periods is not material to our argument, and multiple working interpretations, including additional factors, may be entertained. If the earth is elastic enough to develop a persistent curve in response to seasonal changes, it should respond in a similar way to earthquake slips, deformative movements, changes of rotation, and the like. A correspondence has been noticed between certain sharp turns in the nutational curves and the occurrence of earthquakes, and it has been suggested that sharp changes in the nutational movement may be the cause of the slips that give rise to the earthquakes. I would suggest reversing the reasoning and making the earthquake slips the cause of the sudden turns in the nutational curve. Present data are scarcely adequate for final interpretation of causes, but the nature of the nutation seems to me to afford well-nigh conclusive evidence that no liquid or viscous layer sufficient to afford hydrostatic support to the continents envelops the earth.

THE TESTIMONY OF THE BODY TIDES

The studies of Kelvin[1] and others long ago led to the view that the earth is essentially solid, but this was not accepted as excluding the assignment of the solidity to viscosity. Evidence pointing more specifically toward elastic solidity was added by Schweydar[2] and others. The evidence of elastic control rose to full demonstration in the exquisite records of tidal action secured by Michelson and his associates, Gale and Moulton.[3] Taken all together, these make it quite sure that the earth body acts under tidal stresses as a highly elastic solid. The tidal result has its cause in a complex succession of stresses that come and go gradually. The nutational and the tidal evidences relate to the action of the earth as a whole. They are thus specially fitted for a megatectonic test. Structural material cannot well act elastically as a whole unless its essential parts are elastic. Fortunately there is a specific test that determines directly the elasticity of the parts.

THE TESTIMONY OF THE SEISMIC WAVES

It has long been well known that earthquakes are due to breaks or slips in the rocks of the earth's shell and that they are elastic phenomena. They thus give the penetrating seismic waves good elastic credentials from the very start. At the point of origin, vibrations of practically all kinds to which the rocks are susceptible are generated, but as these vibrations strike through the body of the earth, they are sifted according to the competency of the material to carry them. They also at once begin to be separated according to the speeds that are natural to them, and this betrays their natures. It is now regarded as established beyond reasonable doubt that the second set of preliminary waves are transverse and that they do not pass through liquids or quasi-liquid substances that lack elasticity of form.

Transverse waves have already been found to penetrate the earth along a multitude of paths, and such probings of the structure of the interior are constantly adding fresh testimony. The fact that each of

[1] Lord Kelvin, *Popular Lectures and Addresses*. II. *Geology and General Physics*, "Review of the Evidence regarding the Physical Condition of the Earth" (1879), pp. 258–98; "Internal Condition of the Earth as to Temperature, Fluidity and Rigidity' (1878), pp. 299–318.

[2] *Loc. cit.*

[3] A. A. Michelson and Henry G. Gale, "On the Rigidity of the Earth," *Jour. Geol.*, Vol. XXVII (1919), pp. 585–601.

the deeper waves must twice traverse the horizon of the supposed liquid layer before it can make a record adds to their significance. The ground already fairly well tested by these waves covers a large part of the outer seven-eighths of the earth. They probably pass through the remaining central eighth and will likely be available as evidence later, but as yet the records of this central part are obscure and the interpretations are not yet firm. Unnecessary doubt has been thrown on the records relating to the middle horizons in certain cases by neglect to correct the records for the slowing of the speed due to the increased density of the deeper parts. Records of the best type amply cover the deepest ground assigned to the supposed liquid layer. The records of the transverse seismic waves, therefore, constitute a very specific and searching test. They show not only that the elastic solidity of the earth increases from the surface downward, but that in its outer part the elastic solidity increases relatively faster than density.

Summation.—When the three new lines of geophysical evidence are added to the megageologic evidences offered by base-leveling, sea-transgression, parallel deposition, and periodic megadiastrophism, and when these are considered in connection with the persistent reorganization of the heterogeneous material of the interior made evident by the exudations of all the geologic ages and with the slow glacier-like idiomolecular solid flow prevalent in the interior, as indicated by megadiastrophism, a combination of singular competency is presented. The factors are not only eminently consistent with one another but are singularly well fitted to elucidate the essential features of the earth's megatectonics. These may be put in freer terms:

1. The "floating crust" is a misinterpretation. The continents stand on solid (elasticostatic) foundations. They do not float hydrostatically.

2. The earth is a heterogeneous elastic solid inclosed in a riveted jacket which it has been for ages forming about itself from worn and weathered surface material reshaped and bound together by exudations from within.

3. The most vital agency in the reconstruction of the earth is the reorganization of its heterogeneous material.

4. The earth is better organized and stronger today than ever before, and the reorganizing processes show no signs of exhaustion.

ORIGIN OF INCLOSED MEANDERS ON STREAMS OF THE COLORADO PLATEAU[1]

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ABSTRACT

Meanders more or less narrowly inclosed by canyon walls characterize certain parts of many streams of the Colorado Plateau. On larger streams, the meanders appear to have been inherited from a preceding well-advanced erosion cycle; they are intrenched with inappreciable change of plan where hard rocks immediately underlay the former valley, but are greatly modified or obliterated where weak rocks have been encountered in deepening the valley. On smaller streams inclosed meanders are restricted to parts of the course carved in hard rocks, and their form indicates origin by downward-lateral corrasion, possibly or probably during the present erosion cycle. In soft rocks the tendency to cut horizontally so widens and clears the valley that the stream flows in a very wide shallow channel which is relatively straight. The origin of these features is mainly controlled by the strength of the rocks and relative loading of the streams.

INTRODUCTION

In the course of several seasons of geological investigation in the plateau country of western Colorado, eastern and southern Utah, northwestern New Mexico, and northern Arizona the writer has had opportunity to observe a considerable portion of this remarkable region, the scene of classic researches by distinguished representatives of an earlier generation of geologists: Powell, Gilbert, Dutton, and others. Among the many striking features which mark this land of lofty cliff-bound mesas, great buttes, and forbidding canyons are the topographic form, geographic plan, and general position, with reference to geologic structure, of the valleys of the master-stream, Colorado River, and many of its tributaries. This paper describes briefly certain characteristic parts of the Colorado River drainage, and discusses the origin of inclosed meanders[2] on parts of many streams and the absence of meanders on other parts. In a later study the form of the valleys of the major streams will be considered in more detail, and the conclusions advanced here concern-

[1] Published by permission of the Director of the United States Geological Survey.

[2] In this paper stream meanders that are more or less closely bordered or inclosed by the valley walls are termed "inclosed meanders."

ing meanders will be applied to interpretation of the physiographic history of the region.

THE COLORADO RIVER DRAINAGE

General character.—Colorado River gathers the waters from rains and melting snows on the western slope of the Rocky Mountains, on the San Juan, Uinta, and lesser ranges and, augmented by torrential showers which fall on thousands of square miles of the plateau country during parts of the year, flows swiftly southwestward through nearly continuous deep canyons. It is a perennial stream but one of very unequal volume of flow. During the period of spring floods it is a swollen, muddy torrent, thundering irresistibly seaward. At time of low water, in the late fall and winter months, it is only a thirtieth or a fortieth as large, but is still a very unruly and vigorous stream. Its larger tributaries in the Colorado Plateau, Green and San Juan rivers, are likewise perennial streams of very uneven flow, but the vast number of lesser tributaries are of the intermittent type in which extended periods of dryness alternate with sediment-laden floods.

Topographic form of valleys.—In a few places, notably in western Colorado, where moderately thick, weak-rock formations are exposed, the valley of Colorado River is wide and its sides are gently flaring. Throughout most of the plateau country, however, precipitous cliffs of hard rocks closely imprison the stream. In Cataract Canyon, just below the mouth of Colorado River's chief tributary, the Green, the walls are very steep and high. In Glen Canyon, which extends some 75 miles below Cataract, the river is narrowly inclosed by sandstone cliffs several hunded feet in height. At Lees Ferry in northern Arizona, a zone of upturned soft shale has weathered away so that one may reach the river without descending into a deep canyon, but immediately below the Ferry the waters plunge into the Marble Gorge of Grand Canyon, and for 285 miles the river lies at the bottom of one of the most imposing canyons of the world.

Even casual observations point clearly to the conclusion that the topographic character of the Colorado canyons is essentially dependent on the nature of the rocks in which the river has carved its pathway. Where the rocks are weak, the canyon walls recede; where

they are hard, the canyon is steep-sided and narrow. Though prominent benches or terraces occur in places, as illustrated notably by the Tonto bench and the Esplanade platform in the Grand Canyon, none of these have any significance other than as expressions of the relative strength of the rocks in the places where they occur. This generalization with reference to the Colorado applies equally to its many tributaries, at least in the portion of their courses adjacent to the master-stream.

More detailed consideration of the course of Colorado River and its tributaries calls attention to the fact that in many places the geographic plan is typically that of a maturely meandering stream. However, the meanders are narrowly inclosed by canyon walls which in some places measure more than 1,500 feet high. Because of the profound erosion which marks the plateau province these inclosed meanders are among the most impressive examples of this physiographic feature which can be found. It is the writer's object to undertake a special study of these inclosed meanders.

CHARACTER OF INCLOSED MEANDERS

DISTRIBUTION

Presence on different streams.—Accurate topographic maps of the Colorado and portions of its tributaries that have recently been completed by the United States Geological Survey afford an excellent basis for examination of the character of these stream courses. The Colorado exhibits a rather intricately meandering pattern in eastern Utah above the mouth of the Green (Fig. 1). Major swings from right to left carry the river in a winding course with a meander belt two to four miles wide; secondary meanders complicate the stream pattern. A very interesting double bend that is almost closed is "The Loop," a few miles above the mouth of Green River. Throughout most of Cataract and Glen canyons there are wide-swinging bends (Fig. 2), but the meander pattern for the most part is notably less intricate than above. However, Jefferson[1] notes that the Colorado meanders above Lees Ferry are more pronounced than those of the Mississippi between Memphis and Baton Rouge. Green River has a highly meandering course which is deeply incised in the

[1] M. S. W. Jefferson, "The Antecedent Colorado," *Science*, new series, Vol. VI (1897), p. 294.

rocks of the plateau. The "Bow-knot," 51 miles below the town of Greenriver, Utah, is a striking example of large meander loops which have almost closed to form cut-offs. Inclosed meanders are especially

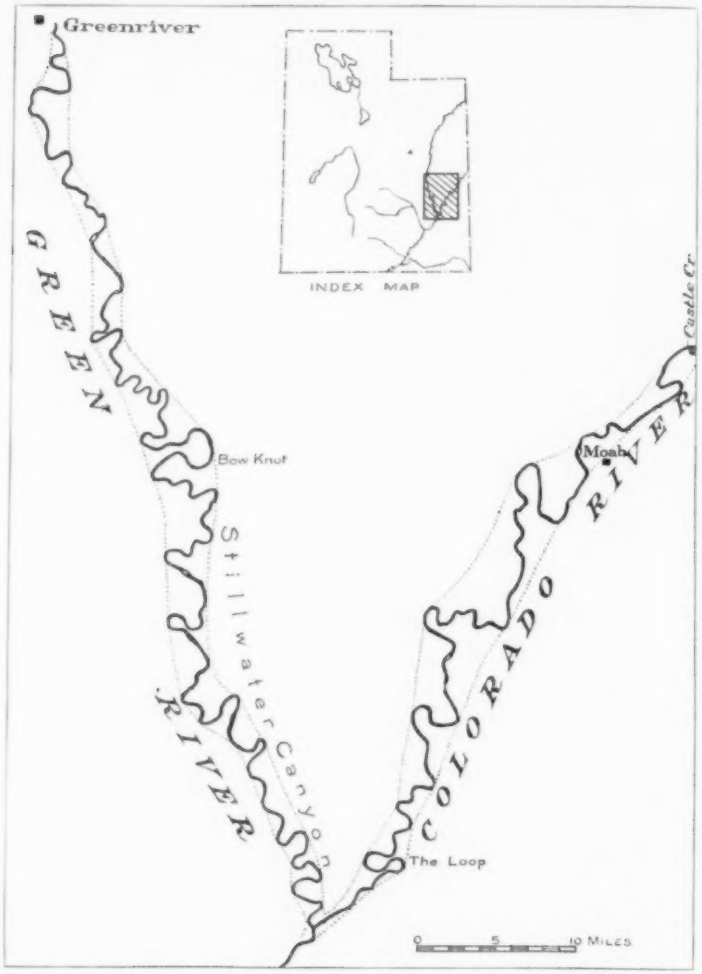

FIG. 1.—Sketch map of a portion of Colorado River above the mouth of the Green, and of the lower part of Green River, Utah.

well developed along certain parts of San Juan River in southeastern Utah.[1] The lower Fremont and Escalante rivers, much smaller

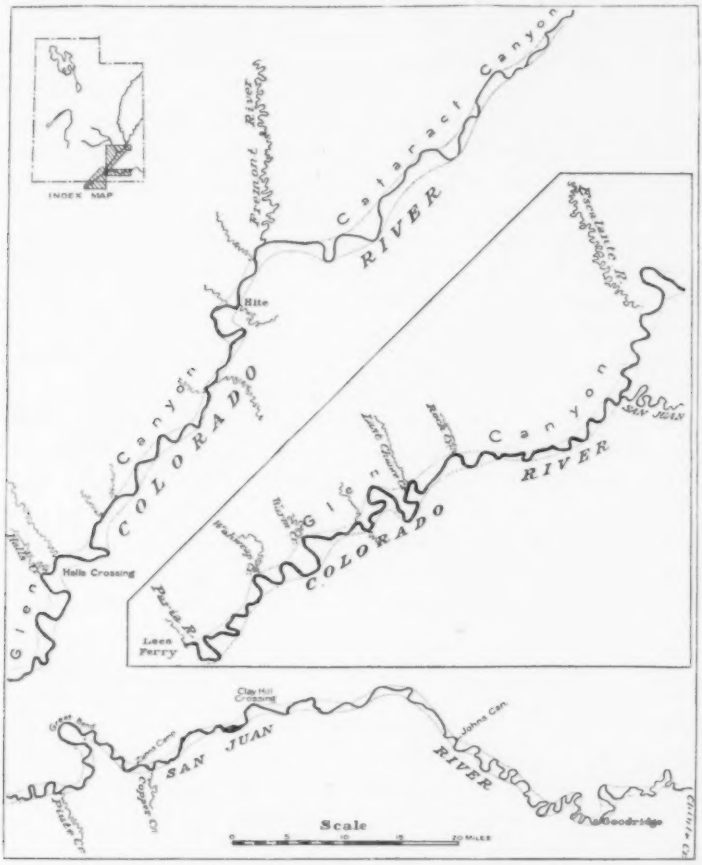

FIG. 2.—Sketch map of a portion of Colorado River and its tributaries in Utah and Arizona.

than the Green or the San Juan, are set in deep, intricately meandering canyons (Fig. 2). Even the short, relatively insignificant tribu-

[1] H. E. Gregory, "Geology of the Navajo Country," *U.S. Geol. Survey Prof. Paper 93*, Pl. 26, 1917, and L. V. Pirsson, *Textbook of Geology*.

tary drainage is characterized to a very large degree by inclosed meanders, the courses of nearly all streams being much more irregular and tortuous than is indicated on any of the older published maps. It appears, then, that more or less deeply trenched meanders are very widely distributed, and that they mark the courses of the large streams and the small.

Position along streams.—Study of the distribution of the meanders emphasizes next that although they are found on almost every stream they are restricted, in reality, to certain parts of the streams. The Colorado swings back and forth around many meanders above the mouth of the Green and in Glen Canyon, but meanders are poorly developed in Cataract Canyon. Above Lees Ferry meanders are very prominent, but below the Ferry the river flows in a nearly straight southwestern course for approximately 40 miles. Beyond this point in Marble Gorge there are two or three evenly rounded meander bends. Farther downstream the river proceeds without marked deviation to the point where it is joined by Little Colorado River and turns westward into the main part of the Grand Canyon. There are several big bends of the river in the Grand Canyon, but none of these appear to be meanders.

On San Juan River the lowermost 40-mile section has a rather notably meandering course with smoothly rounded loops which in several places are nearly closed. One of the most interesting features here is the so-called "Great Bend," in which the river swings in a long sharp loop northwestward toward Colorado River, and though it is only a short distance to the master-stream along a route favored by rock structure, the San Juan turns back nearly due eastward, flowing against the dip of the rocks and circuitously follows a course five times as far to the Colorado. The second 40-mile stretch along San Juan River contains various curves and minor bends, but nowhere are there well-defined inclosed meanders. A third section, approximately 50 miles in length, extending to the mouth of Chinle Creek, is intricately meandering and the river is deeply inclosed in a narrow precipitous-walled canyon. Above Chinle Creek, the mouth of which coincides with the point where an important east-dipping monoclinal fold crosses the river, the San Juan flows in a broad valley essentially without meanders.

The lower courses of Fremont and Escalante rivers, which are carved in sandstone, are extremely sinuous and rather narrowly inclosed by canyon walls, but upper sections on both streams are open and lack meanders.

The numerous minor tributaries show essentially similar characters and may be illustrated by a single example. Warm Creek, an intermittent stream which is dry most of the year, rises in the Cretaceous plateau of eastern Kane County, Utah, and flows southeastward about 30 miles to the Colorado, which it joins at the point where the river crosses the Arizona-Utah boundary. Proceeding up the creek from the river one passes first through a deep, tortuously winding canyon carved in massive Jurassic sandstone. The canyon diminishes in depth as the creek bed climbs to the top of the sandstone, and on reaching the next overlying formation, a rather weak sandstone, the valley becomes wide and the course of the creek fairly straight. For several miles this character is maintained while flanking sandstone cliffs gradually converge upstream toward the creek. This sandstone is crossed in a moderately deep, narrow, rather highly meandering canyon, but on reaching a soft shale at the top of the sandstone the valley becomes again open and fairly straight. Ahead there rises a prominent escarpment of Cretaceous sandstone, and ascending the canyon which Warm Creek has carved in this formation, the course of the stream reverts to its irregularly meandering habit (Fig. 3). The canyon here divides into three main branches, each of which is notably meandering, and the rock walls more or less closely parallel each bend and loop of the winding streams until eventually weak strata are reached above the massive sandstone. Here the pronounced meanders disappear. A still higher, hard, massive sandstone follows, but Warm Creek has only indented its strongly scarped margin. The canyons of other streams which are carved in it have meandering characters similar to canyons in the lower sandstones. It appears that inclosed meanders characterize the portions of the small tributaries which are carved in hard rocks but are lacking in portions where the rocks are relatively weak (Fig. 4). This is true very generally through some thousands of square miles of plateau country.

An attempt has been made to represent graphically the distribu-

tion of meanders on Colorado River and certain of its tributaries, as shown in Figure 5. If, as indicated in Figures 1 and 2, tangents are drawn to the outer bends of meander loops so as to define the

FIG. 3.—Sketch map of portions of the valleys of Warm Creek and Last Chance Creek, southern Utah, showing inclosed meanders carved in hard rocks. From surveys by the writer.

meander belt of the stream, a median line marking the axis of the stream's course may be set down readily. In proportion to the amount of winding of the stream back and forth, distances measured along its course exceed those scaled along the general axis. This excess distance, which is due to the meanders, may be plotted either

directly or in terms of percentage of the axial distance. Thus, the portion of Escalante River shown in Figure 2 has a length of 34.7 miles along the stream, but the excess due to meandering is 20.5

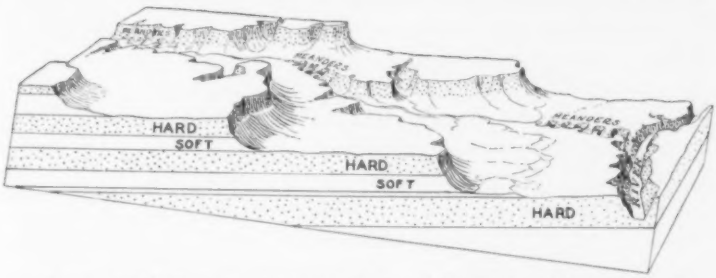

FIG. 4.—Block diagram representing the typical distribution of inclosed meanders on a tributary stream in the Colorado Plateau country.

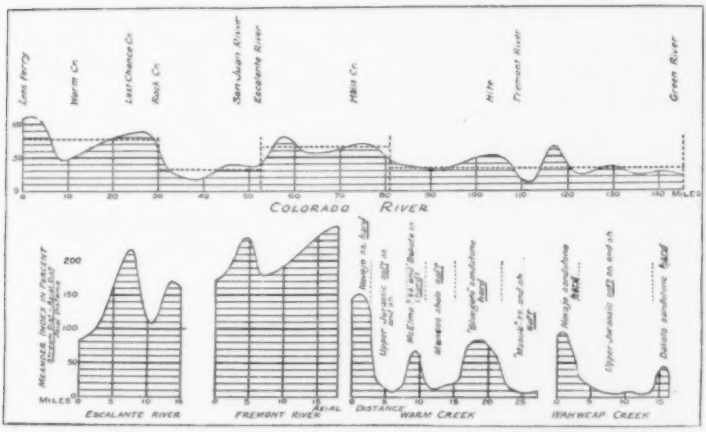

FIG. 5.—Meander graphs of a part of Colorado River and certain tributary streams.

miles, which is 144 per cent of the axial distance, and furnishes a convenient mathematical index of the meandering. In making the graphs shown here averages of 3-mile sections along the stream axis were employed, for, especially in the case of larger streams, a smaller unit gives alternate abnormally high and low values and is less useful in forming a true picture of the distribution and amount

of meandering. The meander graph of a part of Colorado River (Fig. 5) shows the general distribution of moderate but not intricate meanders along the river. Fremont and Escalante rivers have notably high meander indices. Successive large and small meander values along minor tributaries are well shown in the graphs of portions of Warm and Wahweap creeks.

Relation of meander distribution to rock hardness.—The statement concerning distribution of the inclosed meanders and the graphic representation of the meanders show that on each of the streams in the plateau country meander stretches alternate with relatively straight parts of the stream course. In the case of the minor streams this alternation appears to be correlated very closely with the hardness of the rocks that form the successive parts of the valley, meanders being essentially restricted to the hard-rock stretches (Fig. 4). In the case of the larger streams there is no clearly evident correlation between distribution of meanders and strength of the rocks. Cataract Canyon, the San Juan Canyon from Johns Canyon to Clay Hill Crossing, and Marble Gorge are all carved in hard rocks, but the streams lack distinctive meanders such as are present in adjoining hard-rock stretches where in some cases the same hard rocks appear. Soft-rock stretches on San Juan and in places on Colorado River lack meanders, but on Green River and locally in Glen Canyon, where soft rocks form the lower part of the valley, active side-cutting and increase in meandering is observed.

SIZE OF MEANDERS

Inclosed meanders in the Colorado River basin are obviously related to the size of the stream along which they occur. The meanders of the Colorado are wide-swinging curves, each bend or loop measuring several miles in length. On San Juan River they are considerably smaller than those of the Colorado, but larger than those of the Fremont and Escalante, a relation which corresponds to the size of the respective streams. The small tributaries have diminutive inclosed meanders.

A measure of the development of meanders investigated by Jefferson[1] is the ratio of the width of the meander belt to the width

[1] Mark S. W. Jefferson, "Limiting Width of Meander Belts," *National Geog. Mag.*, Vol. XIII (1902), pp. 373–83.

of the stream. An average limiting ratio of 1 to 18, which Jefferson concluded was applicable to flood-plain meanders, is observed not to apply to intrenched meanders, the Colorado being included among examples of the latter which were studied. This meander-belt ratio for the section of San Juan River from Johns Canyon to Chinle Creek ranges from about 25 to more than 75, values which are considerably in excess of the normal flood-plain meander ratio. Following uplift and rejuvenation of the meandering stream, it is obvious that downward-lateral corrasion may increase appreciably the width of the meander belt, and thus modify the ratio derived by Jefferson. However, such widening does not appear to have been effective in the portion of San Juan River here under discussion and it appears that a much more important factor is the narrowing of the stream's channel which is due to the resistance of the rocks in which the canyon is carved. Owing to the very uncertain value of the various factors that are involved, and because, in many cases, of a not inconsiderable subjective element in setting down the meander-belt width, the writer concludes that observations of this ratio have comparatively little value.

FORM OF MEANDERS

In considering the form of the inclosed meanders along the Colorado and its tributaries attention may be directed first to the shape of the meanders in horizontal plan and secondly to the general topographic character, particularly the relative slopes of the confining rock walls (Fig. 5). It is particularly important to discriminate evidence of lateral corrasion and shifting during intrenchment and to make record of any features which afford information concerning the streams which flowed in the valleys before their intrenchment.

Geographic plan.—Most of the meanders on Colorado River are large curves which suggest the sinuous body of a crawling snake; the average radius of the meander curvature is large, and the arc relatively small. These features mark an intermediate stage between incipient and advanced meander development. In some places, however, meander loops are almost closed, so that a small amount of side-cutting would make cut-offs. The average meander value for the entire stretch included in Glen and Cataract canyons

is approximately 50, stated in terms of the percentage of excess of river distance over axial distance, but some parts are more strongly meandering than others. The meanders of the San Juan are not unlike those of the Colorado in plan, excepting the section between Johns Canyon and the mouth of Chinle Creek, which presents an unusual series of closely crowded, well-rounded loops. The meander patterns of Fremont and Escalante rivers are more intricately tortuous than those of any other streams of the region, unless exception of certain of the lesser tributaries is made. The meanders on these streams are of the compound type, secondary curves and bends having been added to complicate a more simply meandering course.

Topographic form.—The walls of the meandering sections of Colorado River are very steep for the most part, both on the convex and concave sides of the curves, and in some sections they rise precipitously 1,500 feet from the river-level. In the inclosed meanders of middle Marble Gorge the river is approximately 2,800 feet below the rim, which, with the cliffs below, follows closely the curves of the river. Some of the meander bends in Glen Canyon show clear indications of a certain amount of lateral cutting in the essentially vertical cliffs along the outer and downstream curves of the river, and slip-off slopes on spurs which project into the meander bends. Figure 6 shows some of these meanders below Halls Crossing. Study of the canyon topography here indicates, however, that lateral shifting has modified only slightly the character of the meanders which existed before intrenchment; this modification has consisted chiefly in sweeping the meanders slightly downstream, little in widening the meander belt. The general steepness of the ends of the projecting spurs (Fig. 7) shows clearly that vertical corrasion has been strongly dominant and lateral corrasion relatively unimportant.

The meanders on San Juan River are similar to those of the Colorado in that very little or no decrease in the steepness of the slopes of the inclosing walls is observable at the points of spurs projecting into meander bends. This is most clearly seen in the inclosed meanders of the section between Johns Canyon and the mouth of Chinle Creek (Fig. 8), where there is no appreciable evidence of lateral shifting of the meanders during the downward corrasion.

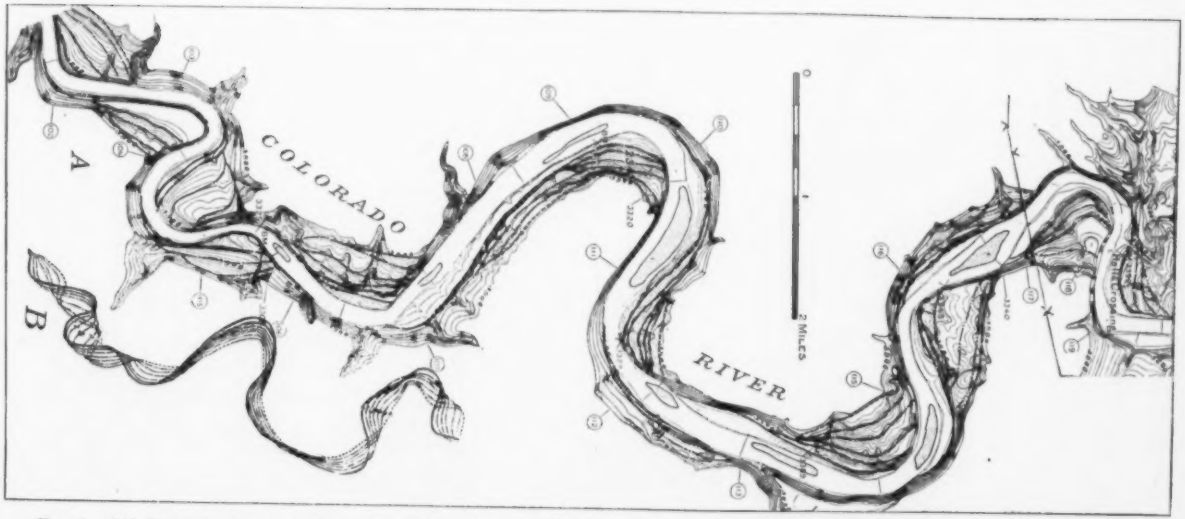

FIG. 6.—(A) Topographic map of a portion of Glen Canyon below the mouth of Halls Creek showing inferred position of meander scaurs at successive 100-foot elevations above the river. Topography not shown above the 3,900-foot contour. (B) Diagram representing inferred changes in the course of Colorado River in the portion of its valley shown in A.

The inside, convex walls of the meander bends on the lower river and at the Great Bend are practically as steep as the outer concave walls, though a small amount of meander shifting has occurred in the sand-

FIG. 7.—Intrenched meanders of Colorado River just above Lees Ferry, Arizona, looking southeast.

stone in which the river is here carved, as appears in the same formation in the adjacent part of Glen Canyon. This is shown by the slightly asymmetrical shape of the projecting spurs and a very slight development of slip-off slopes upon them.

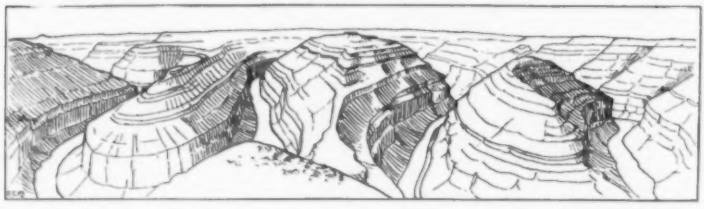

FIG. 8.—Intrenched meanders on San Juan River below Goodridge, Utah. The meander belt is here a little over one mile in width and the canyon is about 1,300 feet in depth (after Gregory).

Most of the inclosed meanders of Fremont and Escalante rivers and of the small tributaries exhibit well-developed slip-off slopes on the spurs which project into meander bends, and more or less strongly undercut cliffs on the outer and downstream walls of the bends. In seeking to cross such meandering canyons one quickly finds that

access to the stream bed may be gained by descending one of the more or less gentle slip-off slopes, and that egress from the canyon may be made by climbing one of these slopes a short distance up or downstream. A striking example of downward-lateral cutting is afforded by Muley Twist Creek on the east side of the Circle Cliffs, southern Utah, in which widening meander bends undercut the sandstone in places so as to form huge caves into the mouths of which the ends of the opposite slip-off spurs project (Fig. 9). In some cases the slip-off slopes are only partially developed, the upper parts of the canyon walls showing typical marks of downward-

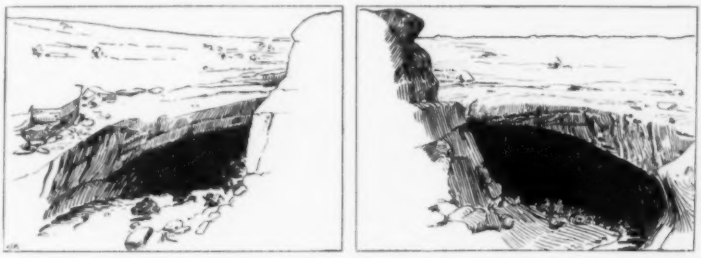

FIG. 9.—An undercut meander on Muley Twist Creek. Sketches looking into large cave formed by downward-lateral corrasion at a meander bend; views from each side of opposite slip-off slope. The rocks are hard sandstone that dip toward the observer.

lateral cutting, while the lower parts are eroded downward with walls of essentially equal slope on the two sides of the stream at the bends.

Study of the topographic form of the inclosed meanders indicates that (1) those of the larger streams are inherited from a meandering course which antedates the intrenchment, even though a certain amount of lateral shifting has occurred in some places; (2) those of the smaller streams are the work of downward-lateral cutting which is now in active progress and which is possibly referable to a single cycle of erosion; and (3) those of streams of intermediate size, like the Fremont and Escalante, are probably inherited from pre-intrenchment flood-plain meanders but have been so modified by lateral shifting that origin is not clearly determinable.

ORIGIN OF INCLOSED MEANDERS

TYPES OF INCLOSED MEANDERS

As indicated by representative textbooks in common use, and in other geological writing, it is commonly inferred that inclosed meanders have inherited their plan from an earlier physiographic stage, when a meandering course was a normal accompaniment of the gently sloping graded plain on which the stream flowed. The inclosing walls of the meanders indicate relatively recent active vertical corrasion and mark the actual or relative elevation of the country in which the valley has been carved. The winding valleys have been called intrenched meanders or incised meanders somewhat indiscriminately and interchangeably.

In 1893 Winslow[1] called attention to the form of certain meandering valleys of the Ozark region in Missouri, and suggested that by lateral cutting along the outer bends of moderately small sinuosities meanders were developed during the process of intrenchment. Davis,[2] whose illuminating contributions to the knowledge of stream work are most numerous and important, has critically analyzed the manner in which various features of inclosed meanders are developed. In earlier papers, certain meandering valleys which clearly exhibit evidence of lateral shifting during downward corrasion are regarded as simple inheritances from an old peneplain, though indication of meander widening is recognized. A later essay[3] calls special attention to the rôle of lateral corrasion during downward erosion, by means of which inclosed meandering valleys may be developed by streams that originally had only slight irregularities in their courses. Davis suggests that the term "incised meanders" may be applied to inclosed meanders developed in this way, and that "intrenched meanders" may be restricted to those formed by re-

[1] Arthur Winslow, *Science*, Vol. XXII (1893), pp. 31, 32; Vol. XXIII, pp. 152–53.

[2] W. M. Davis, *Science*, Vol. XXI (1893), pp. 225–27; Vol. XXII (1893), pp. 276–79. "Rivers and Valleys of Pennsylvania," *Nat. Geog. Mag.*, pp. 183–253, 1889. "River Terraces in New England," *Bull. Mus. Comp. Zoöl.*, Vol. XXXVIII (1902), pp. 281–346. "The Seine, the Meuse, and the Moselle," *Nat. Geog. Mag.*, Vol. VII (1896), pp. 189–202, 228–38.

[3] W. M. Davis, "Incised Meandering Valleys," *Philadelphia Geog. Soc. Bull.*, Vol. IV (1906), pp. 1–11.

juvenation and dominant downward corrasion only. Tarr[1] has recently called attention to these presumably distinct types of intrenchment, describing examples of each and urging use of the terms "incised" and "intrenched" in the restricted sense suggested by Davis. An excellent discussion, seemingly overlooked by Tarr, has been published on these valley forms by Rich.[2] In this contribution the term "ingrown meanders" is applied to the valleys which have undergone notable lateral shifting during intrenchment. Physiographic factors chiefly involved in development of the valleys are considered and interpretations connected with physiographic history are outlined in some detail.

It should be emphasized, the writer believes, that the distinction of these two types of meandering valleys can by no means be sharply drawn, and it is not at all a reliable basis for inferences that physiographic history in the one case is different from that in the other. As observed by Davis and others, inclosed meanders of the so-called incised or ingrown type may readily develop during the downward corrasion of an antecedently meandering stream. The contrasting types described by Tarr[3] occur in the same physiographic province and are separated but a short distance in miles. Outstanding examples of these two types, selected for illustration by Rich,[4] represent two portions of the same stream which likewise are separated from each other by only a short distance. These observations indicate that the differences are due rather to variation in conditions during the corrasion than to unlike physiographic histories.

On the basis of these various observations we may set down the following conclusions. (1) In the case of many meandering valleys there is certainly indicated an interruption of one more or less well-advanced erosion cycle, the rejuvenation of erosive energies, and a certain amount of progress in a second cycle. Corrasion may be dominantly vertical, but may have also a lateral component. (2) Many meandering valleys appear to have been developed by down-

[1] W. A. Tarr, "Intrenched and Incised Meanders of Some Streams on the Northern Slope of the Ozark Plateau in Missouri," *Jour. Geol.*, Vol. XXXII (1924), pp. 583–600.

[2] John L. Rich, "Certain Types of Stream Valleys and Their Meaning," *Jour. Geol.*, Vol. XXII (1914), pp. 469–97.

[3] *Loc. cit.*

[4] *Loc. cit.*

ward-lateral corrasion of a stream having only minor initial sinuosity, and such valleys may be formed in a single erosion cycle. (3) There is a gradation between these two types and they appear to represent variation in the relative effectiveness of the different factors in stream-cutting, rather than essential differences in physiographic history. (4) In a restricted sense, the term "intrenched meander" may be applied where corrasion in a meandering stream has been dominantly vertical and "ingrown," or "incised meander" where lateral cutting has been an important element. If a special designation for this valley form is desirable, the writer prefers Rich's term, "ingrown," because it is more truly descriptive of the manner of development. A meander cut downward mainly, but with some lateral shifting, may appropriately be called an ingrown intrenched meander, or, in a non-committal way, any meander more or less narrowly inclosed by valley walls may be termed an "inclosed meander."

FACTORS IN THE DEVELOPMENT OF INCLOSED MEANDERS

As pointed out in the concise analysis of stream erosion by Gilbert,[1] the factors of volume, gradient, load, and rock-hardness are all very importantly involved in the development of the various features of stream valleys. With reference to inclosed meanders, Davis, and subsequently Rich, have called attention to the interrelation and varying effectiveness of downward corrasion which deepens the valley, of lateral corrasion, which extends the meanders and widens the valley, and of sweep, the gradual shifting of meanders down the valley.

Volume.—Unlike the average humid-climate stream, that of the plateau country is subject to very large and frequent variation in volume. The smaller streams are almost entirely of the intermittent type in which nearly all of the erosion is accomplished by torrential floods. The waters of these floods move downstream with velocities that are augmented in proportion to the size of the flood. The erosive energy of a large volume of swiftly moving, heavily laden water is an extremely effective agency in carving the stream valley, cutting downward and, in places where it is thrown against canyon

[1] G. K. Gilbert, "Geology of the Henry Mountains," *U.S. Geog. and Geol. Survey of the Rocky Mountain Region*, pp. 99, 1877.

walls, as at bends of the stream, also sideward. The larger streams of the plateau district are perennial but they are also subject to marked change in volume, so that the erosion accomplished varies widely from time to time. The flood waters appear to have chief importance in shaping the valley, but the flow at lower stages accomplishes also a great amount of work in erosion and transportation. Consideration of the fact of volume indicates that control of stream work, including establishment of gradient, determination of load, rapidity of erosion, and shaping of valleys is in large part referable to it, and most important are the conditions that obtain when the volume is largest.

Gradient.—The factor of gradient is so adjusted to volume and load, the other main elements determining velocity, that erosion in one part of a river system keeps pace closely with that in adjacent sections. This, of course, results in the development of steep gradients in small tributaries, and of much more gentle ones in the large streams. Gradient is also adjusted to rock-hardness, so that the rate of degradation in alternate hard and soft sections is approximately equalized. Therefore, the profile of each plateau stream shows a succession of steps consisting of alternating steep stretches in hard rocks and gentle ones in soft rocks. High gradients occur most commonly along underloaded streams, where accordingly, erosion tends to cut downward; however, a stream in a narrow hard-rock canyon with moderately steep gradient may, because of its load, cut laterally as well as downward, so as to develop rather intricate inclosed meanders. Low gradients normally contribute to the development of meanders, for transportation capacity is reduced until downward cutting becomes small and the inertia of the water swinging against the sides of the channel erodes laterally. Spreading of a stream in a broad shallow channel may reduce the effectiveness of side-cutting even in times of high water, while in low water there may be overloading and deposition, sometimes accompanied by braiding. In such cases meanders are not developed. Gradient is controlled in some parts of the main streams of the Colorado Plateau by bowlder dams formed by the débris brought down by steep tributaries. In certain cases such dams may affect the gradient for many miles upstream, so that it is essentially unrelated to the hardness of

the rocks in the canyon. Miser[1] describes this condition in San Juan Canyon.

Load.—Downward corrasion is dominant in an underloaded stream, and underloading is in general favored by steep gradients, large volume, and by resistant rocks in the floor of the valley. Following an uplift which rejuvenates stream erosion, gradients are steepened and the dominance of vertical cutting tends to impress on the new valley the pattern inherited from the earlier stage. A stream meandering on a flood-plain may accordingly intrench its meanders. The tendency to corrade sideward and down-valley-ward assuredly is not lacking in a meandering stream which is actively corrading its bed, but the erosion tending to widen the meanders and to move them downstream may be overbalanced and effectively masked by the dominance of downward cutting.

When a stream becomes loaded essentially to capacity vertical cutting is impeded and the rôle of inertia in carrying the sediment-laden waters against the outer and downstream borders of the meander bends becomes important or relatively dominant. If the load is relatively large, and especially if it consists in part of coarse material which is rolled and slid along the stream bed, there is a blanketing effect which partly protects the bed, and even though the amount of grit-loaded, rapidly moving water in contact with the sides of the valley is less in amount than that covering the bottom, the effect of the erosion on the unprotected side walls which is thus produced is relatively very important. In a stream with inherited meanders the bends are widened and there is a development of slip-off slopes on the spurs projecting into the meander bends, while undercut cliffs appear on the outer and downstream sides of the bends. In the case of a stream with only slight initial irregularity, a series of more or less regular and strongly defined meander loops may be developed. If downcutting is relatively very slow, the horizontally acting components of erosion tend to widen the valley and clear it of projecting obstructions. Therefore, a controlling factor in the development of inclosed meanders appears to be the relative loading of the stream.

[1] H. D. Miser, "The San Juan Canyon, Southeastern Utah," *U.S. Geol. Survey, Water Supply Paper 538*, pp. 58–71, 1924.

Rock-hardness.—In view of the observations which have been presented concerning the distribution of the meanders on streams in the Colorado Plateau country, it is desirable especially to consider the effect of differences in rock-hardness on the development of meandering valleys.

Taking up first the case of intrenchment of a maturely meandering flood-plain stream, we may observe that where hard rocks underlie the stream valley the meander pattern of the corrading stream tends normally to persist with little essential change, the degree of persistence depending on the strength of the rocks and the relative amount of underloading in the stream. The hard-rock walls of the deepening valley more or less effectively resist the tendency toward horizontal cutting, more, of course, as the rock walls increase in height, for any shift in the position of the stream imposes the necessity of removing increasing quantities of the resistant imprisoning rocks. In crossing the hard rocks, gradient is increased and the width of the stream is constricted until the additional cutting power, due to increased velocity, equalizes the rate of downward corrasion to that in adjoining areas of soft rock with gentler gradients. Colorado River is very much narrower, deeper, and swifter in the Granite Gorge and in hard-rock stretches of Marble Gorge than in parts of its canyon carved in weaker rocks. San Juan River is only 50 feet wide in narrows of the hard-rock gorge near Goodridge, but in some of its weakrock stretches it is as much as 3,300 feet wide.[1]

A fully loaded stream, carried with gentle gradient across a section of soft rock, becomes underloaded as its velocity increases in traversing a succeeding section of hard rocks, and accordingly the tendency toward vertical corrasion is increased and may be dominant in the latter. If the entire course of meandering streams should be let down upon hard rocks the meander pattern should persist without much change, for in general the stream would be only partially loaded and vertical erosion would dominate. However, in a long stretch of rocks of moderate resistance to erosion, the stream may become sufficiently loaded to bring into play a relatively important tendency toward lateral cutting, in which case a more or less pronounced horizontal shifting of the stream course may accompany

[1] H. D. Miser, *op. cit.*, p. 48.

downward corrasion. A stream that is cutting laterally as well as downward in a part of its valley where moderately resistant sandstones are exposed should lose most of its side-cutting tendency on passing to very resistant limestone or granite, since the stream would increase its velocity and become dominantly downcutting. In hard rocks, therefore, it may be anticipated that an initially meandering course will be preserved during intrenchment, with or without much modification, depending on the strength of the rocks and the degree of loading of the stream.

In the case of meander development by downward-lateral cutting the hardness of the rocks is clearly an important factor, since ingrown meanders are characteristically found in hard-rock stretches of many plateau streams, but are absent in adjacent soft-rock stretches. The meanders evidently result from the considerable component of side-cutting in the erosion of the constricted, sediment-charged flood waters which are almost wholly responsible for the cutting of the valleys. When meanders have been formed in the hard rocks the strength of the rocks is sufficient to preserve them, the typical slip-off slopes and undercut cliffs showing clearly the manner of their formation.

Where meanders produced by downward-lateral corrasion are very deeply trenched, or where for some reason the stream is less heavily burdened, erosion may become almost wholly vertical and the slopes of the valley equally steep. The large amount of resistant rock which must be removed in order to increase the width of the meander belt appears in this case to exert a controlling influence, inhibiting much lateral shifting. Irregularly winding canyons in hard rocks appear in some cases to originate by the slow shifting from side to side of the main cutting in a stream as it passes from soft rocks where the channel is very broad to hard rocks where it is greatly narrowed. The resistant rocks act as a barrier behind which the stream is held sufficiently to permit side-cutting in the weaker rocks and to shift progressively the position of main erosion as the waters gradually strip away the weak rocks and begin to carve the hard. Once the stream course is established in the hard rocks, it is relatively fixed; side-cutting may accompany downward corrasion

and thus modify the course, or it is possible that cutting may be chiefly downward in the resistant rocks.

Meanders let down in weak rocks apparently do not persist, and the causes of their speedy disappearance will be considered presently. Neither do inclosed meanders of the ingrown type develop commonly in soft rocks. However, if the proper balance between downward and sideward cutting obtains there is no reason why ingrown meanders should not appear in weak rocks or even in unconsolidated materials. Such meanders are, in fact, found where certain steep-dropping streams are cutting pathways through detrital slopes, in bad-land areas, and elsewhere. Good examples may be seen near the head of Rock Creek, Kane County, Utah, and north of the Henry Mountains. As may be expected, these ingrown meanders in soft rocks are rather evanescent topographic forms.

THE DISAPPEARANCE OF MEANDERS

Streams that are narrow, deep, and swift in portions of their valleys carved in hard rock become wide, shallow, and much less swift on entering adjacent soft-rock valleys. This spreading of the stream increases friction with the channel floor and reduces very greatly the powerful upward and downward currents that in the larger streams produce whirls and "boils" and that contribute so largely to effective transportation of rock débris. Because there is much less swift-moving water in contact with either bank, sideward cutting is retarded. Nevertheless, the presence of weak rocks, which is responsible for the spreading, makes erosion relatively easy. Gradient is so adjusted that the rate of downward erosion equals that in the hard-rock stretch next downstream. Underloaded waters in a hard-rock section of the valley upstream may be fully loaded or overloaded on entering the more gently graded soft-rock section, or, if not, load is readily acquired. The stream must quickly reach a condition in which the load is almost, or perhaps entirely, equal to carrying capacity. The inertia of the moving water becomes then an important force which promotes sideward corrasion and sweep. Sideward cutting, in so far as it takes place, adds to the length of the stream's course and, unless compensated, tends to decrease the

gradient, which in turn reduces cutting power. Sweep does not affect the gradient but tends to clear out the valley by removal of the projecting spurs between meander bends. In any case, alteration in the course of the stream may be expected. If the stream had a distinctly meandering course before intrenchment in the soft rocks began, the dominance of horizontal cutting will assuredly modify, and perhaps obliterate, the meanders.

Since the initial geographic pattern of the meanders on a flood-plain, let down by rejuvenation of the stream on underlying weak rocks, is not different from that developed by downward-lateral corrasion in hard rocks, the evolution of the stream course during intrenchment in weak rocks should be practically identical. There is apparently this difference. Alternating hard and soft rocks are presumably beveled off smoothly by the graded stream that develops flood-plain meanders, so that when uplift renews active downcutting, the portions of the valley underlain by weak rocks should not be bordered by hard rocks which would impede or limit the lateral shifting of the stream. When ingrown meanders carved in hard rocks reach soft materials underneath, the position of the stream is for a time fixed by the walls of resistant overlying rocks; eventually, side-cutting in the weak rocks and cliff sapping will free the stream.

As slow downward corrasion proceeds in the soft rocks, erosion in a horizontal direction may be expected to appear mainly, if not exclusively, as sweep. The width of the meander belt bears a certain relation to the size of the stream, and though the invigoration of a gentle flood-plain stream by uplift may induce some enlargement and sideward shifting of the meanders, the steepened gradient contributes particularly to erosion on the down-valley-ward sides of the bends. In the case of ingrown meanders, the spurs that slope down into the meander bends are much less imposing barriers to stream shifting than the loftier side walls. The dominance of sweep tends to clear away projections from the valley sides and to form a more or less broad valley floor that slopes gently downstream in accordance with the stream gradient. In the process of clearing the valley, cut-offs of meanders may take place (Fig. 10), and partly straighten the stream. Most important in modifying or obliterating the pattern of original meanders, however, seems to be the concentration of

cutting at the ends and upstream-facing sides of spurs between the meanders. This action is due to the spreading of the current so that inertia does not carry the stream as a body against the outer banks. Eventually a broad channel or wash is formed that swings from side to side in very gentle curves or that is almost straight. In some places the position of the stream shifts more or less markedly from time to time under influence of deposition and of flood waters. Pronounced widening of valleys in soft rocks and relatively straight,

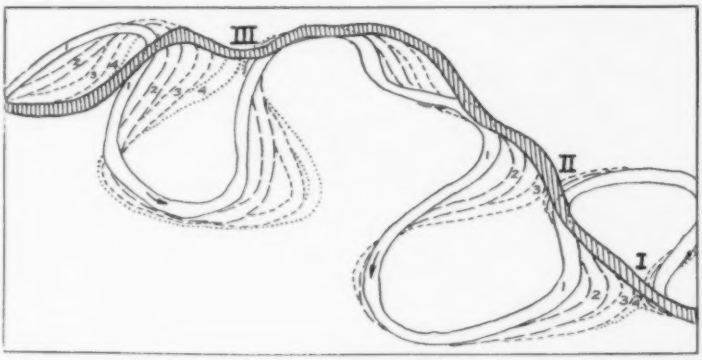

FIG. 10.—Diagram representing possible meander changes in active corrasion of soft rocks with straightening primarily due to cut-offs. An assumed initial stage of typical meandering is indicated by (1), and successive shifts with dominant change in position on the downstream side of meander bends by (2), (3), and (4). The development of a cut-off at (I) causes partial straightening; a cut-off at (II) would deflect the stream into the channel between (II) and (I). A cut-off at (III) would produce further straightening.

wide shallow streams in these valleys are excellently shown in many parts of the plateau country (Fig. 11).

Since throughout the Colorado Plateau soft rocks alternate with hard, the relatively slow downcutting of the hard rocks controls downward corrasion in the soft. The slow lowering of the stream channel in hard rocks is the same in effect as a correspondingly gentle uplift of the section where the stream is cut in soft rocks and, of course, the downward erosion of the hard-rock section is similarly controlled by that of others downstream. The factor of continuous slow downward erosion which is thus given to the stream tends to counterbalance what would otherwise be a dominant tend-

ency to deposit materials in many places and to erode horizontally, forming a wide flat-bottomed valley with many meanders.

In this manner it might be anticipated that the intrenchment of a meandering stream which traverses alternate sections of hard and soft rocks should be marked by sections in the hard rocks where the plan of the original meanders is faithfully retained, the ends of the

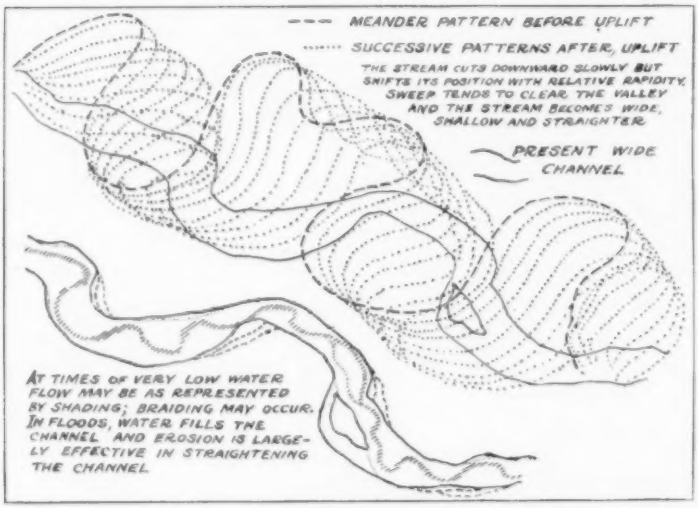
MEANDER PATTERN BEFORE UPLIFT
SUCCESSIVE PATTERNS AFTER UPLIFT
THE STREAM CUTS DOWNWARD SLOWLY BUT SHIFTS ITS POSITION WITH RELATIVE RAPIDITY. SWEEP TENDS TO CLEAR THE VALLEY AND THE STREAM BECOMES WIDE, SHALLOW AND STRAIGHTER.
PRESENT WIDE CHANNEL
AT TIMES OF VERY LOW WATER FLOW MAY BE AS REPRESENTED BY SHADING; BRAIDING MAY OCCUR. IN FLOODS, WATER FILLS THE CHANNEL AND EROSION IS LARGELY EFFECTIVE IN STRAIGHTENING THE CHANNEL

FIG. 11.—Diagram representing hypothetical changes in a meandering stream, flowing from left to right, that is lowering its valley in soft rocks. Straightening is presumably due to clearing the valley of spurs between meander bends by sweep, and the spreading of the stream in a wide shallow channel which flood erosion, in general, tends to straighten by cutting projections of the channel sides.

projecting spurs being steep like the concave outer walls in proportion to the absence of lateral shifting during intrenchment, and in the soft-rock sections it might be expected that the original meander pattern is only partly retained or is lost entirely. Within the broadly flaring sides of soft-rock valleys, little or no evidence of the position of the stream before intrenchment can generally be found. Where ingrown meanders develop by downward-lateral corrasion in hard rocks, these should disappear when the stream cuts through the hard formation into soft rocks.

CONCLUSIONS

1. Very many streams, from smallest to largest, in the Colorado Plateau country have more or less tortuously winding courses, but this character marks only certain parts of the streams.

2. In most places the winding stream is somewhat narrowly inclosed by steep canyon walls that parallel each bend and twist of the stream; this condition is designated by the term "inclosed meander." In some cases, however, streams meander in wide-bottomed valleys.

3. The equal steepness of canyon walls on the two sides of some meandering streams, notably on certain parts of Colorado and San Juan rivers, indicates that the meanders originated before the canyons were carved. Probably the meanders were developed on a flood-plain in an erosion cycle preceding the present, and they have been intrenched by reason of a regional uplift that rejuvenated stream erosion. In a restricted sense, these may be designated "intrenched meanders."

4. Inclosed meanders in the Glen Canyon of Colorado River, in the lower canyon of the San Juan, and elsewhere show a slightly asymmetrical cross-section at stream bends, marking a certain amount of lateral shifting of the stream during the cutting of the canyon. The sideward movement appears to have modified the canyon form and changed the position of the stream course only in small degree, and it is evidently not responsible for the existence of the meanders, which are presumably inherited from an earlier erosion cycle.

5. Green River and parts of the Colorado above Cataract Canyon are eroding weak rocks in the bottoms of their valleys, and, with downcutting retarded by the hard-rock barrier in Cataract Canyon, are corrading laterally, modifying considerably the pattern of meanders which were doubtless inherited from an earlier cycle and which are partly indicated by the position of defending hard rocks above the soft. The meander belt is being widened and cut-offs are imminent in places; sweep is tending to clear away spurs between meander bends.

6. On the Escalante, Fremont, and certain other streams the very prominent slip-off slopes on the spurs projecting into meander

bends and the strongly undercut cliffs along the outer and downstream sides of the bends point clearly to much lateral shifting of the channel during downward corrasion. The meander pattern is remarkably intricate and complex. Meanders were probably inherited from an earlier erosion cycle and have been very much modified by lateral cutting, but it is possible that essentially all of the irregularity of the stream course has been developed during the formation of the present canyon. The meanders are "ingrown."

7. Many small streams show typical "ingrown meanders" in hard-rock stretches and wide valleys with relatively straight but broad shallow channels in soft-rock stretches. The meanders appear to have developed by downward-lateral corrasion during the present erosion cycle.

8. The insignificant effects of lateral cutting in the inclosed meanders of the "intrenched" type, like those on San Juan River below Chinle Creek, appear due to underloading of the stream in these places. Narrowly constricted, and with steepened gradient where the canyon is cut in hard rocks, the stream has increased velocity and relatively decreased load; corrasion is dominantly downward.

9. The effectiveness of sideward cutting in proportion to downcutting seems to be controlled by the relative loading of the stream, especially with coarse material, and the strength of the rocks. This is illustrated by inclosed meanders with varying degrees of prominence of slip-off slopes and undercut canyon walls. With added load there is less tendency to cut downward and more to corrade sideward and forward. The adjustment of gradient to the strength of the rocks, and locally with respect to bowlder dams, largely controls the degree of loading.

10. In hard rocks meanders developed on a graded plain during a previous erosion cycle may be preserved by intrenchment, the geographic pattern of the meanders being practically unchanged. If meanders are formed by downward-lateral corrasion or are modified by "ingrowing" the record of this modification is engraved in the form of the valley.

11. In soft rocks meanders inherited from a previous erosion cycle may be expected to change markedly or to disappear, because

the stream cuts easily and quickly sideward and forward, widening and clearing its valley. Sweep appears to be especially effective in reducing and obliterating spurs from the valley sides. The stream is likely to be overloaded and is prone to spread in a wide shallow channel. Shifting of the main current, and in some cases, braiding, is common; meanders are poorly developed and non-typical or the stream course is relatively straight.

The downward component of downward-lateral corrasion is ordinarily so small that "ingrown" meanders are not developed in weak rocks. This is apparently due to the common heavy loading of the streams in the low-gradient, soft-rock stretches and the accompanying preponderance of lateral cutting which is little opposed by the soft rocks. This, especially through sweep, keeps the valley open and inclosed meanders cannot form.

Under general conditions in the plateau country, therefore, weak rocks are unsuitable for the development or the preservation of inclosed meanders, and it may be anticipated that unless adequately defended by hard overlying beds, stream meanders will be much changed or lost in cutting downward through a weak formation.

THE GROWTH OF ICE CRYSTALS

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ABSTRACT

Present theories of the growth of ice crystals are briefly reviewed. The assumption of Wright and Priestley that ice contains some molecules which move about in the crystals is discussed. An account is given of the method of finding absorption bands in a piece of ice. It was found that the thin region between the ice crystals is highly absorbing. About half of the heat waves were absorbed in the bands of absorption, but in other parts of the infra-red spectrum the layer between the crystals is transparent. This fact is used to explain crystal growth in a solid piece of ice. This theory can be applied to ice in the natural state if proper allowance is made for the existing conditions.

Many of the properties of ice crystals have been studied. Some workers have carried out researches to find the effects of pressure and strains upon ice crystals. Barnes[1] has recorded many of the physical properties. When proper consideration is made for temperature, it is found that ice crystals have properties similar to those of other crystals. For example, the thermal conductivity has a different value in the direction of the optic axis from the value for the direction at right angles to the optic axis. Also, ice is doubly refracting.

In this work a study has been made of the growth of ice crystals in a solid piece of ice. Chamberlin[2] and his fellow-workers have made an extended study of the gradual change of snow into ice. They have pointed out that the rate of evaporation into air cavities from a small crystal is faster than the rate of evaporation from a large crystal. This difference is due to the greater curvature of the smaller crystals. If each crystal refroze the same amount of ice from the vapor per square centimeter of surface, there would be a loss in ice by the smaller crystals and the larger crystals would gain in size in this process. But Chamberlin fully recognizes that in the zone of waste—"the glacier proper"—water derived from the melt-

[1] "Physical Constants of Ice," *Transactions of the Royal Society of Canada*, 1909–10.

[2] *A Contribution to the Theory of Glacial Motion.*

ing of the ice plays an important part in the growth of the ice crystals and in the motion of the glacier.

Some scientists have used this theory to explain crystal growth in a solid piece of ice. If we assume that there is a considerable amount of air between the ice crystals, the same explanation would apply. There is evidence of air between the crystals. When a glacier is melting, the air can be heard escaping. There is no doubt that some air exists in the ice, but it is not likely that there are sufficient air cavities in a piece of ice to give rise to the rapid growth of ice crystals.

If there was present a layer of liquid between the crystals, its vapor pressure would be greater than that of the ice. Also, the vapor pressure of ice crystals of great curvature would be greater than that of crystals of small curvature. Under these conditions the small crystals would disappear while the large ones would increase in size. However, there is a limit to the size to which the crystals will grow. The two theories of crystal growth which have just been outlined depend upon some property of the region between the individual ice crystals. As will be shown later, this inner region has an important influence upon the growth of ice crystals.

Wright and Priestley[1] have offered another explanation of crystal growth. It is assumed that ice is made up of molecules which can move about and other molecules which are fixed in position. The molecules which move about have a higher energy content than the fixed ones. It is further assumed that the molecules which are free to move about are mostly concentrated in the region between the ice crystals. Naturally, the molecules of higher energy content, and which can move through the ice, are the same as molecules of a liquid. So on the basis of a warmer liquid surrounding the ice crystals, Wright and Priestley explain the growth of ice crystals. As the molecules between the crystals lose some of their energy they become a part of the solid ice. The authors of this theory then give a very plausible explanation of how the larger crystals would gain more molecules than they lost and would become larger. In like manner it is explained how the smaller crystals would lose more molecules than they gained and become smaller and finally disappear.

[1] *Glaciology*. London: Harrison & Sons.

If we assume that there is a layer of warmer liquid around the ice crystals, the theory of Wright and Priestley accounts for all the observed facts in crystal growth. It will be shown from the experimental work of the writer that there is no necessity for assuming two kinds of molecules in ice. There are some objections to this assumption. From the work of Sutherland[1] it appears that ice is composed of one kind of molecule $(H_2O)_3$, or trihydrol. Ice has a vapor pressure of about 4 millimeters at 0° C., and this would indicate that ice does contain other kinds of molecules. However, the vapor pressure is probably a breaking down of the ice molecules at the surface. The molecules of higher energy content are supposed to come continuously from the interior of the ice crystals and in a way take the place of those which have rejoined the ice from the boundary region. This would mean that there is present in the interior of the ice a supply of energy which would constantly liberate the molecules. In fact, there would be a slow interior melting. This does not appear to be plausible. However, there is no experimental evidence to uphold these objections; yet there is no experimental work to show that these assumptions are true.

Pure water could not be in contact with ice at temperatures below 0° C. without freezing unless there was a source of energy available to keep the water above the freezing-point. Water could be in equilibrium with ice at lower temperatures if salts were in the water. It is well known that if a piece of ice is exposed to the radiation of the sun or an electric lamp, melting takes place first along the boundaries of the crystals. When both the ice and the surrounding air is several degrees below 0° C., the melting is confined to the crystal boundaries. After a few minutes almost all of the liquid will drain out from between the crystals and they can be removed from the block of ice easily with the fingers. Many geologists have explained the melting between the ice crystals as due to the presence of salts in this region. If the water from which the ice was frozen only contained a small percentage of salt, the concentration of the last part to be frozen would be much higher than that of the first to freeze. That is, the region between the crystals would be richer in salt than in the interior of the crystals. Under these conditions

[1] *Philosophical Magazine*, Vol. L (1900), p. 460.

the boundary region would melt at a lower temperature than 0° C. There is no doubt that natural ice contains some salt.

However, if distilled water is frozen, about the same crystal form appears in the ice. The region between the crystals will melt more rapidly when exposed to radiation than the rest of the ice. It was found that if the water which was drained from between the crystals was collected, its freezing-point was 0° C. If salt is present, the melting would take place more easily; but the salt would not be the cause of the melting.

Since the radiation from the sun or a lamp causes the melting, it is natural to believe that the crystal boundaries must absorb a considerable amount of the radiation which passes through the ice. The writer[1] has recently proved this experimentally. It was found that ice absorbs heat radiation. Melloni and others have made a study of the absorption of heat radiation by ice, but their work did not take into account the dependence of the amount of the absorption upon the wave-length of the infra-red rays. In nearly all materials there is a variation of the amount of absorption of the different wave-lengths. The writer found that ice had several absorption bands in the near infra-red region and that for some parts of the spectrum there was scarcely any absorption. There were two sets of bands: one set when the plane of polarization was parallel to the optic axis and another set when it was at right angles to the axis. A piece of ice made up of two crystals, which had the boundary between them placed at right angles to the incident radiation, showed three sets of absorption bands. The third set of absorption bands was due to the absorption of the boundary region. These bands were located where the individual ice crystals were least absorbing. There was the same number of bands as found for each direction in the individual crystals, but the amount of absorption was much greater. The thickness of the boundary region is only a small fraction of that of the ice. When consideration is made for the thickness, it is found that the boundary region had an absorption coefficient many times larger than that of the ice in the crystals. About 40 per cent of the total radiation was absorbed in the bands, but the part of the infra-red spectrum between the bands was transparent.

[1] *Journal of Optical Society*, November, 1924.

It was thought that further knowledge could be gained about the regions between the ice crystals by studying them with the aid of a microscope. A large block of ice was used as part of the condenser so that the radiation which is absorbed by the ice would not reach the specimen under study. Some of the boundaries between the crystals were found to be .0005 centimeter in thickness. That

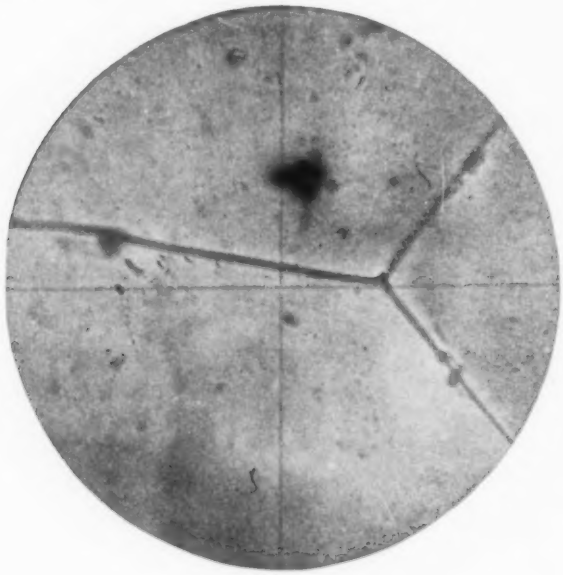

FIG. 1

is, the boundary had melted sufficiently for this thickness of water to be present. The boundary region cannot be seen when no melting has taken place; but on account of the difference of the index of refraction of water and ice, it is easy to detect a layer of water.

In Figure 1 is shown a microphotograph of parts of two crystals with the boundary between them; the magnification is about forty-six times. Some melting had taken place on the surface beyond the boundary but not to a great extent. In Figure 2 is shown the appearance of the boundary after further melting. The magnification here

is about twenty times. When both of these microphotographs were made, the temperature of the ice and the air was several degrees below 0° C. The melting was caused by the radiation from an electric lamp. It is easily seen that the volume of the boundary region is small compared to the ice in the crystals. When the ice is exposed to radiation, the boundary melts rapidly, due to its high

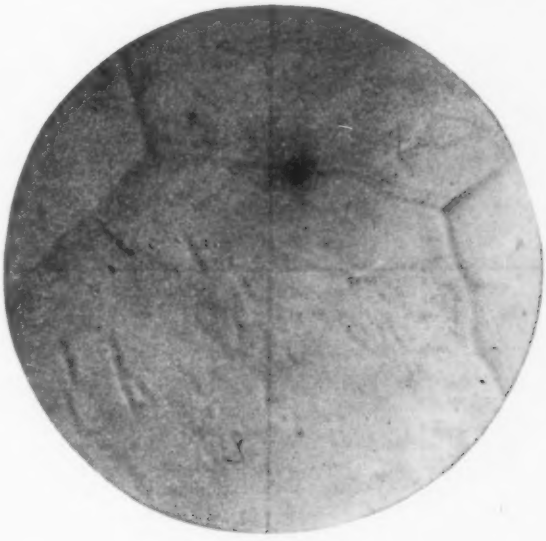

FIG. 2

absorptive power and its small volume. Infra-red radiation is sent out from the sun and at night it comes from rocks, the air, and other sources. Also, infra-red radiation takes place between bodies of low temperatures. So crystal growth will take place at low temperatures.

The next question which is considered is, How does the radiation get very far beneath the surface of the ice? Since about 40 per cent of the radiation in the part of the spectrum where the bands are located is absorbed, the radiation of this part of the spectrum will become very weak after a short distance is traveled in the ice. But after the radiation has continued for some time, all of the ice in the boundary regions which is near the surface will be melted. Then the

radiation can pass through the water and melt the boundary regions at greater depths. In this way the radiation will penetrate to a great distance in the ice. If there are impurities in the ice, they will absorb and radiate some of the radiation passing through the ice.

Ice in the natural state seems to be favored in crystal growth. The radiation is present in the daytime to form the liquid between the crystals; at night, the infra-red radiation is far less. So at night the crystals can gain rapidly from the layer of liquid which was formed in the day. At the time of the year when the radiation is most intense and the ice is below 0° C., we should have the most rapid growth of the crystals. The crystal growth will take place when there is a small amount of radiation present continuously. It is likely that the most rapid growth takes place when there is a sufficient amount of radiation present to melt all of the boundary region, and then the radiation is cut off and the crystals gain in size from freezing this layer. However, the larger crystals will gain more molecules from the liquid per square centimeter of surface and thus the new boundary region will be pushed toward the smaller crystal. This process is repeated each time the boundary region is melted.

Since the absorption of radiation is so different for the region between the crystals and the crystals themselves, it is natural to expect that there must be some difference in the material composing them. As water freezes, the crystals grow in size until their faces come up close to one another. If the optic axes of the two adjacent crystals are in different directions, the crystals will not unite and form one. In that case there will be a layer of small crystals that will not be able to orient themselves properly to join either of the larger crystals. It may be possible that the ice between the crystals is of a different form from that in the larger crystals.

Some of the properties of the region between the ice crystals have been discussed in this paper. This region melts very rapidly when exposed to radiation. This causes a layer of warmer liquid to surround the ice crystals. So the assumption of Wright and Priestley in regard to the two kinds of molecules in ice is not necessary.

In conclusion, the writer wishes to express his thanks to Mr. C. E. Miller, of the Geology Department, for making the microphotographs shown in this work.

THE TIME FACTOR IN THE FORMATION OF SOME ARTIFICIAL MINERALS

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INTRODUCTION

The following notes were given in substance before the March meeting of the Michigan Academy of Sciences, Arts, and Letters, as an abstract of a more extended paper which was presented at the February meeting of the American Ceramic Society, and which is to be printed in the journal of that Society. Since the latter publication is probably not generally known or available to geologists, the writer, at the suggestion of Professor W. H. Hobbs, gives herewith a brief summary of some of its mineralogical and geological aspects.

The minerals were formed in the Dressler tunnel kiln of the Champion Porcelain Company, Detroit, Michigan. It is a continuously operated kiln, in which the ware (porcelain spark-plug cores) is placed on cars and is gradually pushed from the cool entrance end into zones of increasing temperature until a maximum of about 1460° C. is reached. The ware then passes into zones which are gradually cooled by incoming fresh air until it finally leaves the exit at slightly above atmospheric temperatures.

The kiln was in continuous operation at the temperature indicated for a period of eighteen months, up to June, 1924, when it was shut down for repairs. It is unusual that opportunities are offered for the study of mineralogical changes at such high temperatures and over such a long period of time. It is also unusual that with remarkable foresight the owners, previous to lighting the kiln, distributed through it numerous specimens of a ceramic nature in order to observe the effect of the continuous high temperature upon special mixtures as well as upon the actual linings of the kiln itself.

When the kiln was shut down and could be entered, besides the

specimens placed therein, there were found two interesting deposits of artificial minerals which were formed as by-products during the burning. Interesting changes were also noted in the mineralogical constitution of some silicon carbide cylinders, and of the silica brick

FIG. 1.—Lithophysae-like craters of cristobalite formed along the lower right-hand side of the muffle and also on some of the specimens. Practically all of the white material on or within the muffle is cristobalite.

roof of the kiln, and associated with the silicon carbide cylinders there was a structure very closely resembling lithophysae (Fig. 1). In some of these artificial formations there appeared to be evidence of pneumatolytic action having played a prominent rôle. A thorough petrographic examination was made of all the deposits to determine their mineralogical nature.

SILICA GLASS

This was the first artificial mineral noted, and it occurred near the entrance end of the kiln at a point where the temperature was about 500° to 600° C. There were two types of deposit, the more abundant of which formed white coatings, extremely light and fluffy in character, with a smooth outward surface resembling that of a mushroom. In some places it coated the walls of the kiln to a depth of an inch. Deposition was not continuous along the walls, abundant gaps being noted where there was no deposition. A partial chemical analysis showed about 98 per cent SiO_2. Curiously enough, as the temperature increased the deposits disappeared, and in the hottest zones, at temperatures above 1000° C., none of this silica glass was present. This is quite different from what might be expected.

Apparently the deposits were the result of a pneumatolytic action due to an oxidation of the linings in the hot zone which were composed of silicon carbide. Part of the oxidized SiC had remained in place in the form of SiO_2 (cristobalite), but part was probably volatilized and carried along with the other kiln gases toward the cooler entrance end of the kiln. The silica deposits occurred at a point which is known as the "water-smoking" zone; that is, the point at which the chemically combined water of the clay in the ware is driven off as steam. This takes place at about 450° to 550° C. Thus ideal conditions were present for a pneumatolytic action; namely, the gaseous SiO_2 suddenly came into contact with the cooler and powerfully oxidizing water vapor. Were the silicon compound not already fully oxidized, the steam would complete the action, and the sudden contact with the comparatively cool water vapor would cause the precipitation of the SiO_2 in the solid form. The very sudden cooling undoubtedly accounts for it being deposited in the amorphous glassy form rather than in one of the crystalline forms of silica.

HEMATITE PSEUDOMORPHS AFTER MAGNETITE

These were found in the beginning of the cooling zone just beyond the hot zone, coating the roof and upper part of the walls of the kiln where conditions were oxidizing and pressures slightly greater than atmospheric. The deposits in places formed a thin,

closely matted coating of black glistening crystals, and in other places took on branching arborescent shapes composed of crystals in parallel groups. Some of the masses were magnetic, while others were not. Microscopic examination showed them to be mainly hematite, with some magnetite. The form of the crystals is that of magnetite.

According to Hostetter and Sosman,[1] hematite can be formed only below 1000° C. under oxidizing conditions, while above that temperature it gives up oxygen and forms magnetite. From the form of these crystals it is evident that magnetite was first formed and, as it cooled, it absorbed oxygen to form hematite. However, a thermocouple at this point registered about 840° C. It therefore appears probable that the dissociation temperature of hematite is lower than the work of Hostetter and Sosman indicated. It must be remembered here that the time factor is probably much greater than in their experiments, with a consequently greater opportunity from the time viewpoint for the production of equilibrium conditions.

These deposits were also probably due to a pneumatolytic action, the iron derived from the hot framework of the cars as they passed out of the hot zone. As the iron came into contact with the fresh air it would be easily oxidized and part would undoubtedly be carried on toward the top of the kiln with the air and gases, where it would be cooled and would be deposited as iron-oxide crystals in the form of magnetite or hematite, depending upon the temperature. Any moisture in the incoming air used for cooling purposes would increase this action very markedly.

CRISTOBALITE LITHOPHYSAE

Among the specimens placed in the combustion chamber were some bodies composed principally of silicon carbide. The temperature existing at that point was unknown, except that it was considerably higher than the highest recorded in the kiln proper, namely, 1460° C. The result of this exceedingly high temperature was to volatilize the silicon carbide and to convert it under oxidizing conditions to SiO_2 and CO_2. The former in some instances remained behind as cristobalite and formed a white shell of material having

[1] *Jour. Amer. Chem. Soc.*, Vol. XXXVIII (1916), 1188.

the same shape as the original body. At many points, both on the various bodies and along joints between the silicon-carbide muffles themselves, crater-like formations developed, which were composed of cristobalite. In some instances they were an inch in diameter and the same in depth. They presented a striking similarity to lithophysae, except that they were composed of only one rim instead of many. They usually occurred at the mouth of a gas channel through the specimen, or along the joint between the sections of the muffles. The channels themselves were usually lined with a coating of cristobalite, just as cavities in rhyolites and pegmatites are frequently lined with a wide variety of minerals.

Undoubtedly these lithophysae were also formed by a pneumatolytic action involving oxidation. As oxidation progressed along cracks, channels through the bodies formed, and at the mouths of these channels cristobalite was deposited from the gases passing through the bodies. The rims in nearly all cases showed horizontal rings, indicating that deposition was not continuous, but varied as conditions changed from oxidizing to neutral, or reducing, and back again.

OXIDATION OF SILICON CARBIDE AT LOW TEMPERATURES

The most interesting specimens, from the standpoint of the effect of time, were some cylinders of SiC which were scattered along the kiln so that they were exposed to a temperature range from 600° C. to the maximum, which was in excess of 1460° C. Oxidation was prominent in all specimens, and it was usually accompanied by a large amount of swelling, although at the highest temperatures volatilization was very pronounced. Specimens exposed to a temperature of 600° C. swelled to nearly twice their original size, and frequently disintegrated to dust. This was due to the oxidation of SiC to SiO_2. Ordinarily such decomposition does not take place to a marked degree until a temperature of about 1600° C. is reached. It is very apparent, therefore, that the time factor is responsible for this reaction at a temperature about 1000° C. lower.

SILICA BRICK

Of interest also was the change in the constitution of the silica brick used to line some parts of the kiln. Three samples were taken

in such a manner as to show the temperature variation both horizontally and vertically. Thus, at about 1300° C., the brick showed a low quartz, a rather high tridymite, and a large cristobalite content. The latter, however, showed no definite crystallization. At 1460° C. two samples, one taken from the lower walls of the kiln and another from the roof directly above, had the same composition (mainly cristobalite), but the latter sample showed much larger crystals than the former, indicating directly a higher temperature for the roof than for the lower walls. Except for a few crystals of tridymite, cristobalite only was present in both bricks, pointing to the fact that the temperature was practically continuously above the tridymite-cristobalite inversion point. This does not necessarily mean above 1470° C., because the presence of small amounts of fluxes in the brick would materially lower this point.

Many other specimens which were placed along the kiln and later examined gave direct evidence of the combined effect of time and temperature by the increase in size and perfection of development of the crystals formed in them as the temperature increased. In all cases the larger size of the crystals showed a very rapidly increasing rate as the temperature mounted beyond a certain point. Below this point practically no effect was produced as a consequence of the comparatively great time factor. Thus, the crystal growth appeared to show what might be termed a critical point from the standpoint of the time-temperature factor.

The study of the minerals formed in this kiln shows several effects which have been produced at temperatures lower than previously supposed possible, due to the large time factor. The writer believes that in the examples of artificial minerals formed under rather accurately known conditions geologists may see some evidence relating to factors involved in the formation of minerals from magmas or from magmatic solutions.

CONCERNING "EVIDENCE OF LIQUID IMMISCIBILITY IN A SILICATE MAGMA, AGATE POINT, ONTARIO"

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In a paper under the above-quoted title Dr. T. L. Tanton describes an occurrence of quartz porphyry containing globules of a color different from that of the main mass, which globules he regards as the result of unmixing in the liquid state.[1] He refers to a paper in which I described the kind of phenomenon to be expected were immiscibility a fact, and strives to show that in his particular example these phenomena are well displayed.

The pertinent statement made in that paper is quoted by Tanton, but unfortunately only in part. The full statement is as follows, that portion omitted by Tanton being in italics:

> There is only one kind of phenomenon which could be considered as definite proof of the occurrence of limited liquid miscibility, *and it would, without doubt, be very commonly observed if limited miscibility among rock-forming silicates were a fact.* The observed phenomenon would be the occurrence in glassy, or partly glassy, extrusive lavas of distinct globules of material still partly glass, large or small according to their opportunity for aggregation, and of composition different from that of the main mass. Here would lie indisputable proof of the formation of immiscible liquid globules.

Tanton refers to the fact that in a personal communication of February last I expressed my continued adherence to these views, but he might have added that in a similar communication in April those aspects of the matter contained in the italicized part of the above quotation were especially insisted upon as follows:

> Taken literally, your quotation from my paper can be interpreted as you have done, but such was not the intent of my statement. I did not mean that a single manifestation of such a phenomenon would constitute proof of the existence of immiscibility in silicate magmas, but rather that if immiscibility were an important feature of silicate magmas, the observation of this phenomenon would be very common.

[1] *Jour. Geol.*, Vol. XXXIII (1925), 629.

The case against immiscibility must indeed rest on this latter aspect of the matter. It is inevitable that the described kind of evidence of immiscibility would be exceedingly common, and it were folly indeed for me to say that one or even a number of isolated examples of globule-containing masses would constitute proof of immiscibility. A rhyolitic magma, for example, breaking its way up through dacites, could acquire inclusions of dacite that might assume a rounded form, but no proof of immiscibility would lie therein. The supposed examples would require to be related to each other in some systematic way that could be reasonably referred to stages in the process of unmixing, and some logical explanation of the fact that such magmas gave every evidence of complete miscibility in other occurrences would require to be forthcoming.

Evidences of immiscibility of this kind must therefore be of a systematic nature. Considering the ease with which totally fortuitous circumstances might contribute such globules, isolated examples of globular inclusions cannot be regarded as proving anything, though it is quite appropriate that their occurrence should be recorded and their possible significance discussed.

In the case of the globules described by Tanton, I do not believe it is necessary to appeal either to immiscibility or to the inclusion of foreign matter. The specimens which I have seen appear to me to represent a quartz porphyry originally sensibly homogeneous, and of the chocolate-brown color so common for the aphanitic ground-mass of that rock type. This quartz porphyry was permeated by solutions whose principal effect was to change its color to a bright red as a result of the formation of a fine hematite dust (or ferrite, as it is called by Tanton), but without any notable change of total composition.[1] In some of the rock the action of the solutions was interrupted at a time when unaffected portions of the brown porphyry still remained, and, where the rock was massive and structureless, these remnants of unchanged porphyry tended to be of a rounded to globular shape. On the other hand, where the rock was originally more or less banded, the permeating

[1] This conclusion was reached jointly with my colleague J. W. Greig. It was based on a study of specimens which were kindly supplied by Dr. Tanton, and which may, therefore, be assumed as representative.

solutions, again by locally changing the color, naturally emphasized the banding. It is the remnants of unaltered porphyry in their various aspects that Tanton interprets as liquid globules, or as such globules squeezed out into layers and bands.

All the facts given by Tanton appear to be consonant with the interpretation here offered. The analyses of globule and matrix show that they are nearly identical in composition, especially when it is realized that the rock contains phenocrysts of quartz and feldspar, and a very slight inequality in the distribution of these would account for the whole difference found by Tanton. Manifestly, a difference in composition which in all probability depends on such uneven distribution of phenocrysts can have no bearing on the question of immiscibility. Possible unmixing can be entertained at all only when it is proved that the liquid portions themselves were different.

Apart from the slight difference in composition that may be connected with the uneven distribution of phenocrysts, the only difference between globule and matrix is such that it might reasonably be attributed to the hydration and oxidation effect of permeating solutions. Tanton himself points out that in one locality "Small seamlets of agate cut both the black obsidian and the red porphyry, and for a fraction of an inch on either side of their walls the obsidian is bright red." Apparently these seamlets were channels of circulation of solutions and centers from which alteration of the adjoining rock proceeded.

No assurance is to be had regarding a source of the reddening solutions, but perhaps a suggestion will not be amiss. The quartz porphyries of the area are freely invaded by masses of diabase, both large and small. The solutions emanating from these Keweenawan diabases are well known to have the power of producing a red color, not only in the later differentiates of the diabase itself, with which differentiates the solutions are intimately associated, but also in adjacent country rocks. The famous red rocks of Pigeon Point are a conspicuous example, and a number of others have been described. It is suggested that it may have been such solutions that brought about the color-mottling and color-banding effects in the quartz porphyry, for whose explanation Tanton has turned to liquid immiscibility.

GLACIATION IN THE SAN GABRIEL MOUNTAINS, CALIFORNIA

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ABSTRACT

Recently discovered evidence that several glaciers once existed within thirty miles of the site of the business center of Los Angeles is set forth in this paper. The size of the glaciers, the moraines, the amount of ice erosion, a glacial lake-basin, the age of the glaciation, and the factors favorable to the glaciation are all discussed.

INTRODUCTION

The purpose of this paper is to discuss recently discovered evidence for the former existence of glaciers in the San Gabriel Mountains of southern California. As far as known to the writer, no such evidence has been presented heretofore. The chief interest in the glaciation of these mountains lies in the fact that the glaciers existed so far south in the United States. With one possible slight exception (San Jacinto Mountain, California) the former glaciers of the San Gabriel Mountains are to be classed among the most southerly known Quaternary glaciers of the United States. They existed at about latitude 34° 14′ to 34° 20′. Brief mention of some local glacial deposits at a slightly lower latitude in the San Bernardino Mountains, east of the San Gabriel Mountains, was made some years ago by Fairbanks and Carey.[1] More recently the same deposits have been indicated on a geological map.[2]

The San Gabriel Mountains lie north and northeast of Los Angeles. These mountains may in general be looked upon as occupying a nearly east-west, flattened, oval-shaped area about 70 miles long and 25 miles wide. In a broad sense this mountain mass may be regarded as a great uplifted fault-block in a late youthful stage of erosion. The topography is very rugged, owing to the fact that

[1] Fairbanks and Carey, *Science*, new series, Vol. XXXI (1910), pp. 32–33.

[2] University of California, *Department of Geol. Bull.*, Vol. XIII, No. 9.

streams have deeply dissected the uplifted block. The whole mountain group is characterized by numerous steep-sided canyons, many of which range in depth from 1,000 to several thousand feet. Altitudes of 5,000 to 8,000 feet are very common; a number of peaks range in altitude between 8,000 and 9,000 feet or more; while the highest point is the summit of San Antonio Peak (Old Baldy), at an altitude of 10,080 feet.

PINE-FLAT BASIN

The most interesting case of glaciation in the San Gabriel Mountains known to the writer is in Pine-flat Basin, which lies somewhat east of the center of the mountains (Fig. 1). The bottom of this basin is, roughly considered, about $2\frac{1}{2}$ miles long and three-fourths of a mile wide, and it is bounded on three sides—west, north, and east—by an unbroken, steep-sided mountain face from 1,500 to 2,000 feet high. The bottom of the basin is from 4,000 to 6,000 feet above sea-level, while the rim around it ranges in altitude between 5,500 and 8,500 feet. The floor of the basin descends from an altitude of 6,000 feet to 4,000 feet in a distance of $2\frac{1}{2}$ miles. The rocks of the immediate region consist of an older diorite which has been more or less intimately penetrated by a nearly white granite. This mass of mixed rocks is rather highly jointed.

There is good evidence that Pine-flat Basin was once occupied by a glacier with a thickness of at least several hundred feet, a maximum width of at least three-fourths of a mile, and a length of $3\frac{1}{2}$ miles. It started at an altitude of about 8,000 feet and ended at an altitude of about 3,000 feet. The rate of flow of the glacier must have been relatively high because of its steep descent of 5,000 feet within $3\frac{1}{2}$ miles. This is one reason why it pushed its way so far down toward sea-level. It is also a reason why the glacier attained no great thickness in the upper part of Pine-flat Basin.

The principal evidence for the former presence of a glacier in Pine-flat Basin consists in the existence of extensive morainic accumulations. These moraines almost completely mask the bed-rock formations throughout the bottom of the basin. They consist of heterogeneous, unstratified mixtures varying from fine, sandy material to bowlders 5–20 feet in diameter. The bowlders are mostly angular to sub-angular.

Rising above the general level of the glacial deposits there are a number of more or less sharply defined morainic ridges. Among the most conspicuous of these is a narrow ridge 100 to 200 feet high and $1\frac{1}{2}$ miles long in the northern part of the basin on the western side of its floor (see accompanying map, Fig. 1). This is considered to be a lateral moraine. A little to the east of the last-named ridge, and

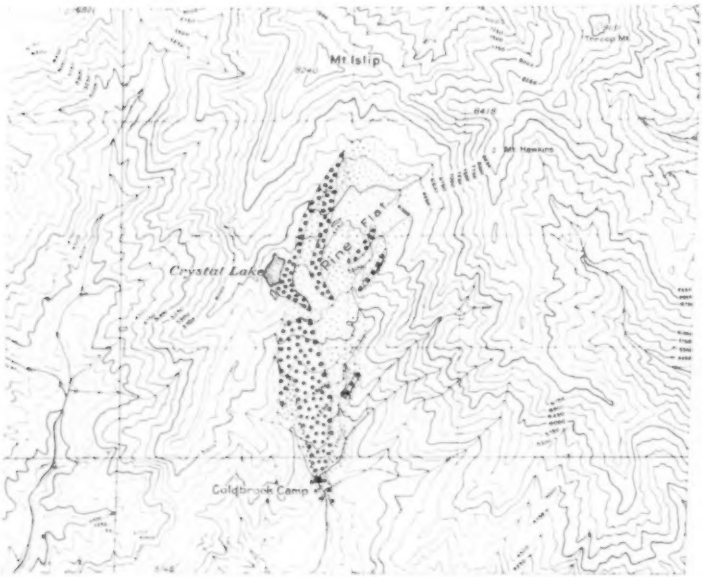

FIG. 1.—Sketch map of Pine-flat Basin and vicinity, showing the location of the principal morainic deposits (dotted areas). The more distinct morainic ridges are indicated by the coarser dots. Square-mile areas are indicated.

joining it on the north, there is another, somewhat less distinct, morainic ridge. This seems to be a recessional moraine. At least two shorter and less conspicuous, parallel, morainic ridges lie in the northern part of the basin on its eastern side.

The prominent ridge one-fourth of a mile wide and several hundred feet high which extends a mile northward from Coldbrook Camp is also a bowlder moraine. Remnants of the former extent of this moraine for one-fourth of a mile south of the Camp still exist, a

considerable portion having been cut away by streams (see accompanying map, Fig. 1). Two short, parallel, lateral moraines lie at the foot of the mountain about three-fourths of a mile north-northeast of Coldbrook Camp. The morainic ridges are, as shown on the map, most prominently developed on the western side of the floor of the basin.

Crystal Lake, which lies near the foot of the mountain on the western side of Pine-flat Basin, occupies the only natural lake basin in the midst of the San Gabriel Mountains (Fig. 2). The lake basin is one-fourth of a mile long and fully 100 feet deep. It nearly always

FIG. 2.—Crystal Lake in Pine-flat Basin. The bowlder-moraine dam shows on the left.

contains water, even in very dry seasons, and it has been known to be filled almost to overflowing. It is quite clearly a moraine-dam lake whose basin was formed where the prominent ridge of lateral morainic material (just described) was locally built across a reentrant angle in the base of the steep mountain side. A smaller dry basin of similar origin lies just south of Crystal Lake.

The principal source of the glacier which occupied Pine-flat Basin seems to have been high up on the west face of Mount Hawkins (see map). Avalanches, particularly on the eastern side of the basin, no doubt made important contributions to the glacier. The main body of the glacier seems to have hugged the eastern wall of the basin much more closely than the western wall, as shown by the

fact that the heaviest morainic accumulations are on the western side.

The relatively large amount of morainic material plainly shows that the glacier was a very active agent of erosion and deposition. One factor favorable to erosion was the large amount of preglacial talus and generally weathered material which must have been present on the lower sides and bottom of the steep-sided Pine-flat Basin. Another factor was the highly jointed character of the rocks.

FIG. 3.—Mount Markham and San Gabriel Peak (in the distance) as seen from near the summit of Mount Lowe. The divide between Bear Canyon and Eaton Canyon may be seen connecting the two peaks.

Postglacial action of running water has caused some of the glacial deposits to be more or less cut into and re-worked. This is especially true in the general vicinity of Coldbrook Camp, where the North Fork of San Gabriel River (locally called Soldier Creek) has deeply trenched the moraine and strewn great quantities of bowlders from it for a long distance in the stream channel. It is in this vicinity that the best sections of the heterogeneous, unstratified, bowlder-moraine deposits are to be seen.

BEAR CANYON

Bear Canyon lies in the southern part of the San Gabriel Mountains, $6\frac{1}{2}$ miles north-northeast of the business section of Pasadena. It has a general east-west trend, and it is tributary to Arroyo Seco

Canyon. It is about $3\frac{1}{4}$ miles long and 1,000 to 1,500 feet deep. The rim of the canyon varies in altitude from over 4,000 feet to over 6,000 feet. The highest points overlook the head of the canyon on the east. Among these are San Gabriel Peak (6,152 feet), Mount Markham (5,800 feet), and Mount Lowe (5,650 feet) (Fig. 3).

The principal evidence supporting the view that a glacier once occupied the upper (eastern) 2 miles of Bear Canyon is the shape of the canyon. This part of the canyon is remarkably straight and

FIG. 4.—View westward down the glaciated portion of Bear Canyon from the summit of Mount Markham.

free from projecting spurs. Its profile is that of a typical glacial trough, the lower portions of whose walls have been covered with considerable talus (see Fig. 4). The contour map does not properly represent it. Its profile is strikingly different from that of the usual canyon in this part of the mountains, although the rocks are of the usual kinds. The rock of the first mile of the presumably glaciated portion of the canyon is diorite, while that of the second mile and beyond is a nearly white granite. The shape of the glaciated portion of the canyon also contrasts sharply with that of the western, non-glaciated portion of the same canyon.

The knife-edge ridge separating the head of Bear Canyon from the head of Eaton Canyon to the east also strongly supports the belief that a glacier once occupied the upper part of Bear Canyon. This striking topographic feature is not well brought out on the con-

tour map. It is particularly well developed for one-third of a mile on Mount Markham, including the summit of the peak (see Fig. 5).

Typical morainic ridges at all comparable to those in Pine-flat Basin were not found, but the bottom portion of the canyon, between 1½ and 2 miles from the head of the canyon, does contain a large accumulation of débris which looks like morainic material consisting mainly of large sub-angular bowlders. Just east of this accumulation of débris there are one or two brushy flats in the bottom of the canyon.

The evidence above presented seems to justify the conclusion that a glacier probably not more than a few hundred feet thick and two miles long once occupied the eastern (upper) portion of Bear Canyon.

UPPER EATON CANYON

The upper end of Eaton Canyon lies just east of the head of Bear Canyon. It heads against the southeastern face of San Gabriel Peak (altitude, 6,152 feet) and the eastern face of Mount Markham in a bowl-like basin one-half of a mile wide across the top and bounded by precipitous walls 1,000 to nearly 2,000 feet high on all sides but the south. From the bottom of the basin the precipitous face of San Gabriel Peak rises nearly 2,000 feet (see Fig. 3), while that of Mount Markham rises 1,500 feet. Some talus material has gathered in the bottom of the basin. This is the most impressive basin of its general kind thus far seen by the writer in the San Gabriel Mountains. Here again the contour lines fail adequately to represent the topography. This basin is separated sharply from the head of Bear Canyon by the knife-edge ridge above described. It is believed that this remarkable bowl-like basin is a true cirque. How could such a basin, so unique in this region, have been developed at the head of the canyon, and the large amount of rock material have been removed, by other than glacial action? It is thought that the glacier which occupied this basin was relatively thick and short—probably several hundred feet thick and less than a mile long.

POSSIBILITY OF OTHER GLACIERS

Careful investigation may reveal evidence for the former existence of glaciers in other parts of the San Gabriel Mountains. The

flanks of Mount Wilson may have supported one or two glaciers. Most likely of all, however, is the high mountain-group in the general vicinity of San Antonio Peak (Old Baldy), but the writer has not examined this region for evidence of glaciation.

AGE OF THE GLACIATION

The former glaciers described in this paper as occurring in the San Gabriel Mountains no doubt existed during Quaternary time.

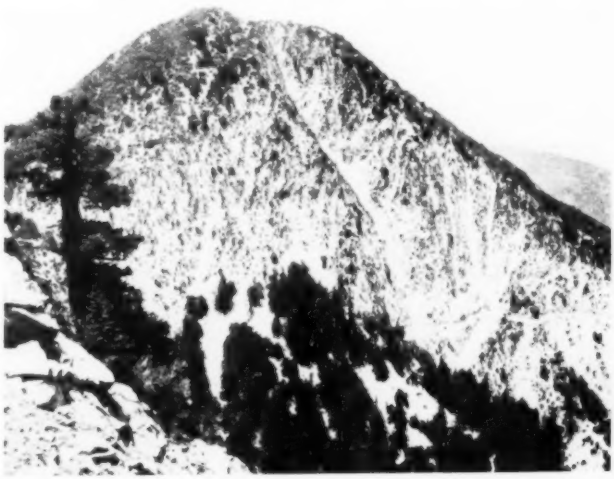

FIG. 5.—View of part of the cirque at the head of Eaton Canyon as seen from near the top of Mount Markham.

Matthes has shown that an interglacial stage intervened between a stage of large, relatively earlier Quaternary glaciers and much smaller late Quaternary (Wisconsin?) glaciers in the central and southern Sierra Nevada Range.[1] The best evidence seems to indicate that the relatively small glaciers of the San Gabriel Mountains existed during the time of the heavier glaciation of the Sierra Nevada Range, and that conditions were not favorable for the development of glaciers during the distinctly later Quaternary. Among the reasons for so believing are the following: deep erosion of portions of

[1] F. E. Matthes, *U.S. Geol. Survey*, Yosemite Quadrangle map (text on back).

the thick glacial deposits in the Pine-flat Basin, and the almost complete shifting of the smaller glacial accumulations in the upper Bear and Eaton Canyons; the degree of weathering of the intact morainic materials in Pine-flat Basin; the degree of postglacial weathering of the glacial canyon walls, resulting in a fairly large accumulation of talus on the lower slopes; and the general absence of polished surfaces and striae.

CONDITIONS FAVORABLE FOR GLACIATION

The upper Bear Canyon and upper Eaton Canyon glaciers were formed in the group of the highest peaks in the southwestern portion of the San Gabriel Mountains. In normal winters of the present time considerable snow falls on these peaks and in the adjacent canyons. It requires no stretch of the imagination to think that, during the coldest part of the Ice Age, the snowfall must have been much heavier, and that the conditions were favorable for the accumulation of sufficient snow to be converted into ice. Then, as now, this group of high peaks was easily accessible to the moisture-laden winds which swept from the Pacific Ocean only 30–35 miles across the wide, low Los Angeles plain.

The region of Pine-flat Basin and its surrounding peaks was considerably farther from the ocean, but this factor was more than counterbalanced by the much greater height of the mountains there. The wide, relatively low opening across the southern part of the San Gabriel Mountains, in part occupied by the main San Gabriel Canyon, afforded a ready passage-way for the moisture-laden winds from the Pacific Ocean. Under present-day conditions snow not uncommonly accumulates to a depth of 2 or 3 feet in Pine-flat Basin and to a greater depth on the surrounding peaks. While this paper is being written, thus early in the season (October 10), the peaks surrounding Pine-flat Basin are snow-capped.

VEINING ALONG FAULTS IN THE PENNSYLVANIAN SANDSTONES IN OKLAHOMA

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ABSTRACT

Many faults in the Pennsylvanian sandstones in Oklahoma have been found indirectly by means of various indications, the most important of which is veining.

The most positive means for determining a fault is to find the displacement of the beds; but often in sandstones, where the beds are very much alike in appearance and there are no ready means at hand for distinguishing one bed from another, a fault can be easily overlooked unless there are some indications present to stimulate a search for the offset. If several similar sandstones are present in an area and the intervals between them vary from a few feet to 50 or 60 feet, a fault of 30 or 40 feet, or even more, can easily be overlooked. One of the greatest difficulties is that faults are often found in, or near, the creek bottoms, where most of the evidence of faulting has been removed or covered.

The Pennsylvanian beds, which cover most of east-central Oklahoma, are made up of a series of sandstones and shales with a few limestones. Quite a number of faults have been found in these beds by more or less indirect methods which it may be of value to describe.

Along the fault planes is evidence of considerable shattering; masses of rock have been crushed and tilted at all angles, and slickensided surfaces are occasionally found. Because of the fracturing, ground waters have moved more readily along the fault zones than through the surrounding rock. Deposition of mineral matter from solution has taken place, and the fractured zones have been recemented in places to form a sort of breccia. The cementing material has, in practically all cases within the writer's experience, been lime.

The recemented pieces of sandstone are often more resistant to weathering than the original sandstone, and because of this, plugs, small ridges, or masses of veined sandstone are found standing alone and projecting above the residual material. In many instances where the beds are red they lighten in color where the solutions have passed, changing from a deep red to a light gray, the iron having apparently been leached from the rock. In places partial calcite deposition has occurred along the cross-bedding planes, where the latter are well defined, forming what might be termed pseudo-veining. The most important indication of the faults, however, has been true veining.[1]

The veins vary considerably in character. The commonest are fine, hairlike veins which crisscross in a network throughout the breccia and stand out on the weathered surface as minute ridges. There are also larger veins which are filled with megascopic calcite crystals and which, in places, reach a thickness of one-quarter inch. Still another type is found in the softer sandstones, where the solutions have deposited their material in a zone about the fracture and cemented the sand grains together to form a vein of limy sandstone instead of deposits of pure calcite along the fracture plane. These sandy veins appear on the surface of the sandstone as rounded ridges from one-fourth to one-half inch wide, with a line running down the middle which represents the original fracture along which the solutions passed. They crisscross, as do the smaller calcite veins, but the mesh of the network is much larger.

Veining is so closely associated with the faults in this region that it can be found along nearly all of them. The direction of a fault is determined by locating several exposures of veining. The offset can then be found by following the beds in the area until they can be correlated and each placed in its proper position.

[1] A. E. Fath, *U.S. Geol. Survey Bull. 759* (1925), pp. 35–36.

A SIX-RAYED *DEVONASTER EUCHARIS* (HALL)

BRADFORD WILLARD
Brown University, Providence, Rhode Island

ABSTRACT

This paper describes an unusual variation in the Devonian starfish *Devonaster eucharis* (Hall).

FORMATION AND LOCALITY

Recently a specimen of *Devonaster eucharis* was brought to the author by one of his students, Mr. W. B. Talman, of Spring Valley, New York. Although Mr. Talman was unable to give the exact locality from whence the fossil came, the author is satisfied that it was collected from the Hamilton "flagstone." It is preserved in a fine gray-to-brownish, muddy sandstone, rather thinly bedded and even grained. The only other fossil present in the slab is half of a valve of a pelecypod some 5 cm. long, and probably belonging to the genus *Grammysia* found associated with *Devonaster* in the Hamilton.

DESCRIPTION

The specimen is an excellently preserved natural cast of the abactinal surface of an animal having an average diameter of 30 mm. The parts preserved are the central disk and six rays. The former is the poorest preserved of all the parts, since it is largely obscured by a deposit of iron oxide.

There seems no doubt as to the identity of the specimen. Upon comparing it with the original description by Hall,[1] and the added remarks of Cole,[2] it agrees in its rather robust body and rays acutely pointed at their tips. As Hall points out, the abactinal surface of the rays shows them to be "composed of three ranges of large, highly convex or tuberculiform plates which are nearly circular at the bases of the rays, becoming quadrate and widened toward the extremi-

[1] J. Hall, *Twentieth Report New York State Cab. Nat. Hist.* (1868), p. 287, Pl. 9, Figs. 3–3a; rev. ed. (1868–70), p. 330, Pl. 9, Figs. 3–3a.

[2] A. H. Cole, *Bull. Geol. Soc. America*, Vol. III (1892), p. 512, Pl. 15.

The recemented pieces of sandstone are often more resistant to weathering than the original sandstone, and because of this, plugs, small ridges, or masses of veined sandstone are found standing alone and projecting above the residual material. In many instances where the beds are red they lighten in color where the solutions have passed, changing from a deep red to a light gray, the iron having apparently been leached from the rock. In places partial calcite deposition has occurred along the cross-bedding planes, where the latter are well defined, forming what might be termed pseudo-veining. The most important indication of the faults, however, has been true veining.[1]

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Veining is so closely associated with the faults in this region that it can be found along nearly all of them. The direction of a fault is determined by locating several exposures of veining. The offset can then be found by following the beds in the area until they can be correlated and each placed in its proper position.

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Recently a specimen of *Devonaster eucharis* was brought to the author by one of his students, Mr. W. B. Talman, of Spring Valley, New York. Although Mr. Talman was unable to give the exact locality from whence the fossil came, the author is satisfied that it was collected from the Hamilton "flagstone." It is preserved in a fine gray-to-brownish, muddy sandstone, rather thinly bedded and even grained. The only other fossil present in the slab is half of a valve of a pelecypod some 5 cm. long, and probably belonging to the genus *Grammysia* found associated with *Devonaster* in the Hamilton.

DESCRIPTION

The specimen is an excellently preserved natural cast of the abactinal surface of an animal having an average diameter of 30 mm. The parts preserved are the central disk and six rays. The former is the poorest preserved of all the parts, since it is largely obscured by a deposit of iron oxide.

There seems no doubt as to the identity of the specimen. Upon comparing it with the original description by Hall,[1] and the added remarks of Cole,[2] it agrees in its rather robust body and rays acutely pointed at their tips. As Hall points out, the abactinal surface of the rays shows them to be "composed of three ranges of large, highly convex or tuberculiform plates which are nearly circular at the bases of the rays, becoming quadrate and widened toward the extremi-

[1] J. Hall, *Twentieth Report New York State Cab. Nat. Hist.* (1868), p. 287, Pl. 9, Figs. 3–3a; rev. ed. (1868–70), p. 330, Pl. 9, Figs. 3–3a.

[2] A. H. Cole, *Bull. Geol. Soc. America*, Vol. III (1892), p. 512, Pl. 15.

ties." The plates are characteristically separated near the arm bases by accessory granules which die out distally. The central portion shows a hexagonal outline rather than the typical pentagonal form, due to the presence of the extra ray. The actinal surface is not represented, but the inframarginal plates are beautifully preserved and visible along the side of the abactinal rows, "making five with the three properly belonging to the upper surface" (Hall). All of the

FIG. 1.—Six-rayed *Devonaster eucharis* (Hall). Geological Museum, Brown University.

plates show a granulose surface, the actinal plates bearing typically three short spines, well-preserved in five of the six points of union of the arms.

ABNORMAL DEVELOPMENT

Schuchert[1] states on this point, "among the 400 specimens of this species [*Devonaster eucharis*] found near Saugerties, New York, there are a few individuals each with but four rays, though otherwise they appear to be of normal development." This, then, precludes the previous description of any six-rayed examples of this species, and the same statement seems equally applicable to the rest of the Paleozoic starfishes. The condition is common in living *Asterias* of our Atlantic coast, in which genus extra arms are often found. The six rays of this Hamilton specimen are equally

[1] C. Schuchert, *U.S. Nat. Mus. Bull. 88* (1915), p. 101.

developed, with no more variation in size or shape than there is between those of the average normal specimen. They do show a slightly stockier build than those of the figured-type specimen, but this the author attributes to their abnormal number. Figure 1 shows the specimen, natural size.

BIBLIOGRAPHY

Palaeaster (part) of authors.

Xenaster (?) or new genus. Gregory, *Geol. Mag.*, Vol. VI (December 4, 1899), p. 346.

Devonaster Schuchert, *Fossilum Catalogus, Animalus*, Part III (April, 1914), p. 14.

Devonaster eucharis (Hall), Schuchert, *U.S. Nat. Mus. Bull 88*, 1915.

REVIEWS

Tertiary and Post-Tertiary Geology of Mull, Loch Aline and Oban. By C. B. Bailey, C. T. Clough, W. B. Wright, J. E. Ritchey, and G. V. Wilson. Memoirs of the Geological Survey of Scotland. Edinburgh: H. M. Stationery Office, 120 George St., 1924. Pp. 445, figs. 66, pls. 6.

The Geological Survey in Scotland has from time to time made contributions to geological literature which, apart from their local significance, have had no small influence on the development of the science. In this relation it is only necessary to recall such memoirs as *The Geological Structure of the North-West Highlands of Scotland* and *The Tertiary Igneous Rocks of Skye;* the memoir under notice worthily carries on the tradition and in some ways is not the least remarkable of the series. It is essentially an explanation of the one-inch map, Sheet 44, of the Geological Survey, but for convenience accounts of other districts in the adjacent sheets 43, 51, and 52 are also included. Descriptions are given of the history of the research, the sediments with their fossil plants, the igneous rocks, the post-igneous history of the district—preglacial, glacial, and postglacial—and the economic geology, unfortunately of minor importance, while a comprehensive bibliography shows the extent to which this classic area has figured in geological literature.

The main interest of the memoir lies in the exceedingly detailed account given of the Mull volcanic center. This center became active in Tertiary times, the first episode being the quiet outpouring of olivine-rich basalts (3,000 feet thick)—the so-called plateau types—followed by a similar development of basalts poor in olivine: the Central types. During the later phases of lava-extrusion the volcanic center probably assumed the form of a gentle Kilauea dome with a central caldera which, as inferred from the presence of pillow lavas in the pile, was filled with water during periods of inactivity. The lavas are pierced by a series of early basic sills and plugs succeeded by large acid intrusions of granophyre, felsite, and augite-diorite, the change from basic to acid magma being accompanied by explosive activity and a consequent considerable development of volcanic agglomerate.

Thereafter, the volcanic history as related in the memoir is mainly one of a complex of intrusions, with volcanic agglomerates, remarkable not so much from the purely petrographical standpoint as from their form and symmetrical arrangement about an axis running northwest to southeast and joining two centers of igneous activity approximately $2\frac{1}{2}$ miles apart. The most interesting of these intrusions are undoubtedly the cone-sheets and the ring-dikes.

The cone-sheets, so called because they occupy a series of "co-axial, cone-shaped fractures with inverted apices united underground," are grouped around the two centers referred to above, the earlier group dipping at angles of 30°–40° toward the southwest center, the later group dipping at similar angles toward the northwest focus. The earlier group is divided into (*a*) an acid and intermediate series consisting of felsites, granophyres, and craignurites, and (*b*) a basic series consisting of olivine-dolerites; the later group consists of quartz-dolerites and tholeiites. Individual sheets are from 15 to 40 feet thick and the aggregate thickness of the basic members of the early group is about 3,000 feet, that of the later group 2,000–2,400 feet. An interesting and constant feature of the cone-sheets of intermediate type is their composite nature, consisting as they do of craignurite, i.e., a rock of andesitic affinities, in the center, with margins of dolerite and tholeiite. Associated with the cone-sheets and apparently more or less coeval with them are large pipelike and sheetlike masses of gabbro and granophyre.

The ring-dikes, so called from their curved or arcuate outcrops, occupy vertical or steeply inclined ringlike fissures grouped more or less concentrically about the same centers as the cone-sheets. Unlike these, however, they frequently show marginal assimilation of the adjacent country rock instead of marginal chilling against it. They are coarser in grain than the cone-sheets and range in type from gabbro, quartz-gabbro, and dolerite, to granophyre and felsite.

The earlier group of ring-dikes is controlled by the southwest center and consists of a series of more or less concentric intrusions separated by screens of older igneous rock, either lava or intrusion. They date from the early part of the second phase of cone-sheet intrusion and are remarkable as showing, in the opinion of the authors of the memoir, evidence of gravitational differentiation of a magma *in situ*. The type example is the Glen More ring-dike, in places as much as 500 yards wide and with a continuous, curved outcrop traceable for 6 miles. It consists of quartz-gabbro with subordinate granophyre. A detailed description is given of one locality where there is a gradual upward transition from gabbro

or dolerite (Sp.G. = 3) to granophyre (Sp.G. = 2.55) over a vertical range of 1,500 feet. Detailed petrographical accounts, with chemical analyses, of the extreme and intermediate types are given and the conclusion is drawn that the dike affords a clear instance of the gravitational separation of early crystals and residual magma and is not an example of the injection into a hot, newly consolidated, basic rock of an acid magma giving rise to hybridization, as described by Dr. Harker in *Skye*. It is well to remember, however, that the Glen More ring-dike is one of a large number of concentric intrusions consisting of granophyre, felsite, or gabbro, which were apparently supplied from a magmatic reservoir or reservoirs capable of furnishing these types ready-made. There is the further point that the section described cuts obliquely across the outcrop of the dike toward its inner margin and it is not clear from the descriptions whether concentric variation within the intrusion is not present. It is clear, for instance, that about 2 miles southeastward from the type locality the outer margin of the dike consists of granophyre. A short description is furnished of this occurrence (pp. 314, 322), where, apparently, granophyre is found at the lower levels and gabbro, 1,000 feet higher up, with transition types. It is to be regretted that this occurrence has not been subjected to the same rigorous petrographical and chemical investigation as the one where the reverse relation holds good.

The second group of ring-dikes is arranged round the northwest center. They consist of granophyre and felsite and are the latest large-scale intrusions in the Mull complex. One of them, the Loch Bà felsite, is perhaps the most perfect ring-dike hitherto described. It varies in width from ¼ mile to 100 yards and it forms a large, practically continuous, closed curve nearly 5 miles across at its widest part around the northwest center. Clear and conclusive evidence is cited that the line of this dike, the latest of all the Mull ring-dikes, is one along which large-scale subsidence took place.

The final stage of igneous action in Mull was marked by the intrusion of dykes of basalt similar in type to the plateau-basalts which were poured out at the commencement of volcanic activity. The dikes of Mull form a swarm, the members of which trend in a general northwest direction. This swarm or belt is in places 12½ miles wide and contains dikes of an aggregate thickness of 2,500 feet. The complex was built up during a long period of time and comprises many petrological types, but it is clear, as already mentioned, that many of the basic dikes are the latest intrusions in the island.

Thus, in its lengthy volcanic history Mull presents two magmatic

cycles of basic to acid types with a reversion to basic type as the final episode. This magma-sequence is explained on the hypothesis that the main reservoir was charged on three separate occasions with parental magma of plateau-basalt type and that the cycles of major activity outlined above resulted from progressive variation during long continued crystallization. The third charging of the reservoir gave rise to the latest basalt dikes.

An interesting feature of most of the igneous rocks surrounding the two centers is the general type of alteration, or pneumatolysis, which they have suffered. This manifests itself by the absence of fresh olivine, and a large development of chlorite, albite, and epidote in the vesicles with concomitant albitization of the basic felspars in the body of the rock. Certain vesicular zones in the lavas are also characterized by an extraordinary abundance of lime-rich zeolites, such as scolecite associated with prehnite and epidote. This peculiarity is ascribed in general to solfataric action arising from the igneous center, but although the altered state of all the lavas is thus explained it is admitted that some of the late basic cone-sheets were probably altered and albitized during the period of cooling of the sheets themselves (pp. 300–301). It seems probable that some of the lavas owe their present state to the same cause, as one well-marked zone, characterized by albite, epidote, scolecite, extends well beyond the limit of general alteration.

Other subjects dealt with are a series of alkaline intrusions, syenites, bostonites, and trachytes, and an interesting set of sills in southwestern Mull which seem to be independent of the main igneous center, and which are remarkable for the peculiar xenoliths present in some of them.

This memoir is a veritable mine of information which is not too easily extracted by the reader. The names of no fewer than sixteen authors appear on the title-page and the labor of welding into a harmonious whole such a large number of separate contributions must have been extremely difficult. Some of the chapters, particularly the petrographical ones, are clear and coherent, but not infrequently the descriptions are disjointed and the praiseworthy desire of the editor to give every contributor his due by inserting the initials of those responsible after each particular statement in the text has not helped the continuity of an essentially complicated story.

W. F. T. McLintock

The Osteology of the Reptiles. By SAMUEL WENDELL WILLISTON. Arranged and edited by William King Gregory. Cambridge: Harvard University Press, 1925. Pp. xiii+300; 191 figures. $4.00.

At the time of his death Dr. Williston had nearly completed a work on reptilian osteology which was to sum up his vast knowledge of this field, gained from a half-century of research. The nearly completed manuscript and a number of illustrations were turned over to Dr. Gregory, who undertook the task of preparing the work for publication and, as it proved, the still harder task of finding a publisher. This has been at last accomplished, and it is to the honor of the Harvard University Press that they have at last put in print a work for which students in this field have long waited.

As the book stands, it is, as nearly as possible, the work of Williston alone. There are a few lacunae; manuscript was lacking for the description of the skull in the dinosaurs, pterosaurs, rhynchocephalians, and nothosaurs, and the taxonomy of the stegosaurus. A few additions and corrections necessitated by recent work have been added in brackets.

The book is divided into two sections. The first, of some 200 pages, describes the reptilian skeleton, structure by structure, and is illustrated by a large number of figures, many by Williston's own hand. In the Introduction the similarity of the primitive reptilian and amphibian skeletons is emphasized, and a useful classification of the skeletal elements is given. The skull takes up nearly a third of the book. First its shape and the openings are treated, followed by a description of the component bones, and finally a discussion by orders. A thorough description of the vertebrae is given, followed by an account of the ribs and sternum, with a discussion of the nature of the ventral ribs. The girdles are described in detail. Under the heading of "The Limb," the treatment of the carpus and tarsus is of especial interest.

The second section treats of the classification of reptiles. It is an elaboration—with considerable modification—of the system proposed by Williston in this *Journal* in 1917, and presents many interesting features. A division into five subclasses is made, mainly on the basis of temporal openings. Under the Anapsida are ranged the Cotylosauria and Chelonia, with an intermediate provisional order for *Eunotosaurus*. The Synapsida include the Theromorpha and Therapsida. The term "Pelycosauria" is restricted to the Sphenacodontidae. A subclass new in Williston's classification is that of the Synaptosauria, erected for the Sauropterygia and

Placodonts, and defined mainly by the presence of a single temporal opening bounded below by post-orbital and squamosal. His subclass Parapsida, founded by him for the Squamata and Proterosauria, is enlarged by the addition of the Ichthyosauria and Proganosauria. The Rhynchocephalia are included in the Diapsida, but their striking dissimilarity to the typical members of the subclass are recognized by the erection of a superorder, Diaptosauria, for them, in contrast to the Archosauria.

Despite the lapse of years and the fact that the author was unable to carry the work through its final stages, the book stands as a monument to Williston's broad and first-hand knowledge of the group, and is destined long to remain the standard work on reptilian osteology.

A. S. R.

A Critical and Experimental Study of Drew's Bacterial Hypothesis on $CaCO_3$ Precipitation in the Sea. By C. B. LIPMAN. Carnegie Institution of Washington, Pub. 340, 1925, pp. 181–91.

Many attempts have been made to explain the origin of precipitated $CaCO_3$, calcareous muds, and oolitic deposits since Murray and Irvine in 1889 explained the precipitation by the interaction of $(NH_4)_2 CO_3$ and $CaSO_4$. The most recent hypothesis of wide acceptance is that of Drew, who, on the basis of experiments at the Tortugas laboratory, ascribed the phenomenon to a specific denitrifying organism which he named *Bacterium calcis* (later determined by Kellerman and Smith as *Pseudomonas calcis*). It should be noted that Drew worked with media rich in nitrogeneous compounds and organic acids, in part in combination with calcium.

In 1920 Lipman began studies upon bacteria in sea-water at Tutuila, especially their kinds and ability to precipitate $CaCO_3$ from pure sea-water. From a series of critical experiments he concludes that "all the bacteria [possibly 32 species] isolated by me can precipitate $CaCO_3$ from sea-water if certain salts are added to the medium." He states further, "In no case was I able to note the precipitation of any calcium carbonate from the [pure] sea-water." These conclusions seem to be diametrically opposed to those of Drew.

Lipman emphasizes the fact that huge calcareous deposits may be the reworked remains of animals and plants. Furthermore, precipitation of $CaCO_3$ would result from appropriate chemical and biochemical reactions, such as the action of $(NH_4)_2CO_3$ on $CaSO_4$, disturbance of equilibrium

conditions involving $Ca(HCO_3)_2$, or increase in alkalinity of sea-water. These ways seem wholly adequate to Lipman without any participation by bacteria.

To these conclusions may be added the opinion of Vaughan that *P. calcis* is largely a bottom-living form where organic matter is present, and thus "it seems that he [Lipman] has not conducted experiments under conditions which would simulate those under which the particular kind of deposit, whose cause is sought, is known to occur."

Hence it appears that the solution of this important problem in sedimentation awaits further critical experimental data.

ARTHUR BEVAN

The New England–Acadian Shore Line. By DOUGLAS W. JOHNSON. New York: John Wiley & Sons. Pp. 628; figs. 273. Cloth, $8.50.

This second major contribution by Professor Johnson to the study of the border-zone of land and sea is not only a most valuable addition to the literature of geomorphology, but it also throws interesting light on the historical geology of northeastern America, on apparently anomalous features in the distribution of plants, and problems of sedimentation. While the book is addressed primarily to physiographers and geologists, the author has in mind also the interest of the engineer and lawyer, the botanist and zoölogist—of "all who love the sea." The work is a carefully detailed and somewhat exhaustive application of the principles and criteria developed in the author's earlier writing, *Shore Processes and Shore-Line Development*, to a selected section of complicated shore line. An advance summary and a résumé at the beginning and end, respectively, of each chapter, and the use of appropriate headlines throughout the text assist the reader in following the elucidation of shore features, but the abundance of well-chosen illustrative material contributes most to a ready comprehension and appreciation of the discussions presented. The photographs are attractive and the features which they are intended to show are evident; the maps are very clear and neatly drawn; especially effective are the block diagrams. Excellent presswork conforms to the high standard of this publisher and is not least important in making a favorable first impression on the reader.

In attacking the subject of the New England–Acadian shore line Professor Johnson first classifies it as a "shore line of submergence," and recognizes in it three main subdivisions: (1) the shore line bordering the resistant uplands; (2) the shore line bordering the weak-rock lowlands; and (3) the shore line bordering unconsolidated débris, mainly glacial

deposits. Part I of the book is devoted to discussion of the "initial form" of the coast, the effects of minor oscillations of level, and the significance of rectilinear segments of the shore line. Part II presents an extended analysis of shore-line evolution in the three main subdivisions, involving in each case a study of: (*a*) the forms produced by wave erosion upon the coast; (*b*) the forms produced by the constructive action of the waves; and (*c*) the hidden submarine forms adjacent to the coast. Finally, the rôle of tides in shore-line development is considered, and tidal marshes in the region under investigation are described and their origin explained.

Reviewing critically the conclusions of other investigators of New England–Acadian shore-line features, the author presents the results of his own studies, which may be summarized in part as follows:

Submergence of the eastern coast of North America is progressively greater to the northeast, its minimum in the Maine region amounting to more than 1,200 feet. The fishing "banks" or submarine plateaus extending from Cape Cod to Newfoundland represent a drowned cuesta of the Atlantic coastal plain with typical steep scarp facing the crystalline old-land and gentle back slope descending to the edge of the continental shelf. The Gulf of Maine is the submerged "inner lowland" between the banks cuesta and the crystalline old-land of New England. The Triassic lowland, whose partial submergence makes the Bay of Fundy, extends southwestward under the Gulf of Maine, and it is bordered on the northwest by a submarine escarpment connecting with that on the northwest side of the Fundian depression and marking the position of the major fault between the Triassic and crystalline rocks.

Minor oscillations of level have apparently been superimposed on the major differential submergence, but in the last few thousand years there has been no appreciable change in the relative position of the sea and land.

Modification of the shore-line by wave work has been slight, on the whole. It is naturally greatest in places where unconsolidated glacial débris forms the coast, as in the Cape Cod region, and least where resistant crystalline rocks meet the sea. The broad and shallow submerged platform bordering the Gaspé Peninsula and the shores of the St. Lawrence embayment, that have commonly been interpreted as due to extensive wave erosion, were much more probably formed above sea-level by normal subaerial erosion, then submerged and very slightly modified by marine agencies.

Straight, even shore-lines that most frequently have been attributed to fracturing or faulting of the earth's crust are shown to result from a variety of causes among which faulting is one of the rarest.

A multitude of shore features, such as spits, bars, and tombolos, are described and illustrated, involving in part considerable repetition. The evolution of Cape Cod and the glacial islands to the south, most interesting examples of work by shore processes, is discussed in detail.

In bringing together and interpreting the wealth of data that is found in *The New England–Acadian Shore Line* Professor Johnson has performed a notable service to physiographic science. To the reviewer, the only weakness worthy of notice is the organization of the discussion. In outlining his subject the author has evidently aimed to trace, somewhat in historical fashion, the making of the present shore-line. Yet, in pursuing this development, the various threads of the discourse are repeatedly dropped, to be picked up again in some later part of the book. Particularly in the chapters on wave-built and submarine forms bordering the different subdivisions of the shore line are difficulties encountered, and there is much apparently unavoidable repetition. Resistant uplands, weak-rock lowlands, and unconsolidated deposits occur in such relations to one another along the coast and from land to sea that features due to one modify or mask those due to others. Thus the author is led to description of submerged weak-rock lowlands, such as the Gulf of Maine, and Fundian depressions in one chapter simply because they happen to border crystalline uplands. Logically, this and other parts of the subject do not seem to belong here. It is true that the complicated interrelations of different elements in the problem present inherent difficulties in the way of a wholly consecutive and logical analysis.

Some of the illustrations seem to be incomplete or inaccurate. For example, in the map of the Gulf of Maine (Fig. 144) the author classes as crystalline old-land the Triassic and Carboniferous weak-rock lowlands, though he differentiates the submerged part of the Triassic. This map, which is especially interesting, would be improved, it seems to the reviewer, by making more evident the relation of submarine to subaerial geologic features.

RAYMOND C. MOORE

A Brief Critical Revision of the Fusulina Species Recently Described, with Additional Studies on Japanese Fusulinae. By YOSHIAKI OZAWA (Tokyo, May, 1925). Journal of the Geological Society. Vol. XXXII, No. 380.

A Japanese paleontologist revises some of the species of Japanese fusulina which have been described or pictured by recent investigators. He also redescribes a number of species.

D. G.